# Availability and Maintainability Benchmarks

## *A Case Study of Software RAID Systems*


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# Overview

- **Availability and Maintainability are key goals for modern systems**
  - and the focus of the ISTORE project
- **How do we achieve these goals?**
  - start by *understanding* them
  - figure out how to *measure* them
  - *evaluate* existing systems and techniques
  - *develop* new approaches based on what we've learned
    - » and measure them as well!

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  - *develop* new approaches based on what we've learned
    - » and measure them as well!
- **Benchmarks make these tasks possible!**

# Part I

## Availability Benchmarks

# Outline: Availability Benchmarks

- **Motivation:** why benchmark availability?
- **Availability benchmarks:** a general approach
- **Case study:** availability of software RAID
  - Linux (RH6.0), Solaris (x86), and Windows 2000
- **Conclusions**

# Why benchmark availability?

- **System availability is a pressing problem**
  - modern applications demand near-100% availability
    - » e-commerce, enterprise apps, online services, ISPs
    - » at all scales and price points
  - we don't know how to build highly-available systems!
    - » except at the very high-end
- **Few tools exist to provide insight into system availability**
  - most existing benchmarks ignore availability
    - » focus on performance, and under ideal conditions
  - no comprehensive, well-defined metrics for availability

# Step 1: Availability metrics

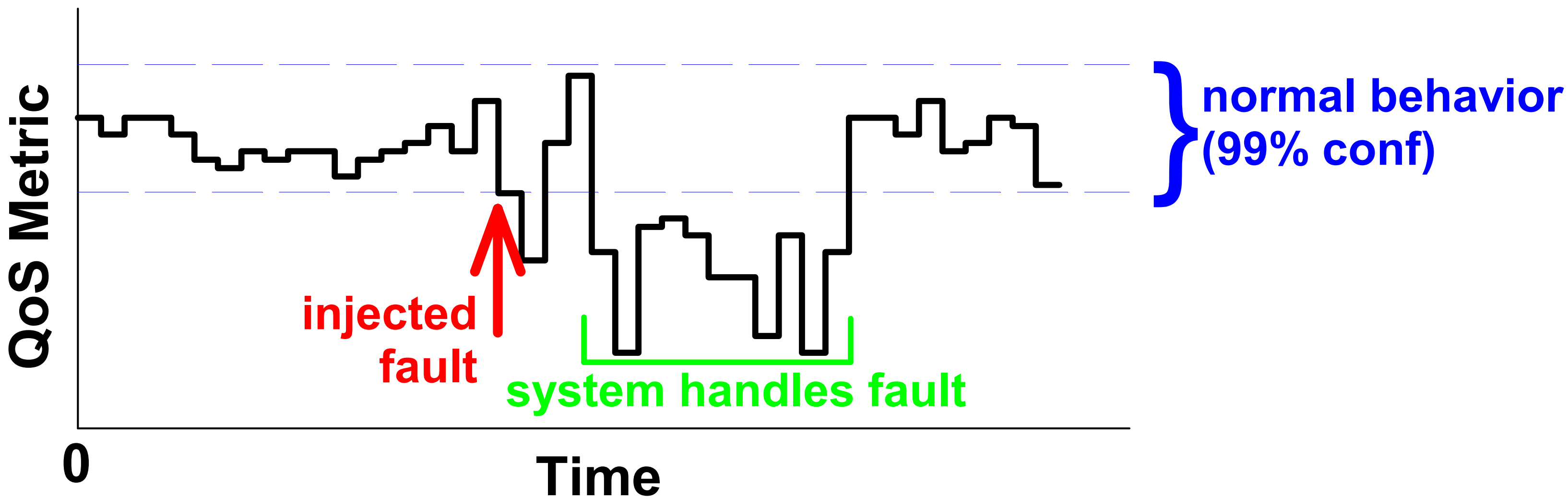
- **Traditionally, percentage of time system is up**
  - time-averaged, binary view of system state (up/down)
- **This metric is inflexible**
  - doesn't capture *degraded states*
    - » a non-binary spectrum between "up" and "down"
  - time-averaging discards important temporal behavior
    - » compare 2 systems with 96.7% traditional availability:
      - system A is down for 2 seconds per minute
      - system B is down for 1 day per month
- **Our solution: measure variation in system *quality of service* metrics over time**
  - performance, fault-tolerance, completeness, accuracy

# Step 2: Measurement techniques

- Goal: quantify variation in QoS metrics as events occur that affect system availability
- **Leverage existing performance benchmarks**
  - to measure & trace quality of service metrics
  - to generate fair workloads
- **Use fault injection to compromise system**
  - hardware faults (disk, memory, network, power)
  - software faults (corrupt input, driver error returns)
  - maintenance events (repairs, SW/HW upgrades)
- **Examine *single-fault* and *multi-fault* workloads**
  - the availability analogues of performance micro- and macro-benchmarks

# Step 3: Reporting results

- **Results are most accessible graphically**
  - plot change in QoS metrics over time
  - compare to "normal" behavior
    - » 99% confidence intervals calculated from no-fault runs




- **Graphs can be distilled into numbers**

# Case study

- **Availability of software RAID-5 & web server**
  - Linux/Apache, Solaris/Apache, Windows 2000/IIS
- **Why software RAID?**
  - well-defined availability guarantees
    - » RAID-5 volume should tolerate a single disk failure
    - » reduced performance (degraded mode) after failure
    - » may automatically rebuild redundancy onto spare disk
  - simple system
  - easy to inject storage faults
- **Why web server?**
  - an application with measurable QoS metrics that depend on RAID availability and performance

# Benchmark environment

- **RAID-5 setup**
  - 3GB volume, 4 active 1GB disks, 1 hot spare disk
- **Workload generator and data collector**
  - SPECWeb99 web benchmark
    - » simulates realistic high-volume user load
    - » mostly static read-only workload
    - » modified to run continuously and to measure average hits per second over each 2-minute interval
- **QoS metrics measured**
  - hits per second
    - » roughly tracks response time in our experiments
  - degree of fault tolerance in storage system

# Benchmark environment: faults

- **Focus on faults in the storage system (disks)**
- ***Emulated disk*** **provides reproducible faults**
  - a PC that appears as a disk on the SCSI bus
  - I/O requests intercepted and reflected to local disk
  - fault injection performed by altering SCSI command processing in the emulation software
- **Fault set chosen to match faults observed in a long-term study of a large storage array**
  - media errors, hardware errors, parity errors, power failures, disk hangs/timeouts
  - both transient and "sticky" faults

# Single-fault experiments

- **"Micro-benchmarks"**
- **Selected 15 fault types**
  - 8 benign (retry required)
  - 2 serious (permanently unrecoverable)
  - 5 pathological (power failures and complete hangs)
- **An experiment for each type of fault**
  - only one fault injected per experiment
  - no human intervention
  - system allowed to continue until stabilized or crashed

# Multiple-fault experiments

- **“Macro-benchmarks” that require human intervention**
- **Scenario 1:** reconstruction
  - (1) disk fails
  - (2) data is reconstructed onto spare
  - (3) spare fails
  - (4) administrator replaces both failed disks
  - (5) data is reconstructed onto new disks
- **Scenario 2:** double failure
  - (1) disk fails
  - (2) reconstruction starts
  - (3) administrator accidentally removes active disk
  - (4) administrator tries to repair damage

# Comparison of systems

- **Benchmarks revealed significant variation in failure-handling policy across the 3 systems**
  - transient error handling
  - reconstruction policy
  - double-fault handling

- **Most of these policies were undocumented**
  - yet they are critical to understanding the systems' availability

# Transient error handling

- **Transient errors are common in large arrays**
  - example: Berkeley 368-disk Tertiary Disk array, 11mo.
    - » 368 disks reported transient SCSI errors (100%)
    - » 13 disks reported transient hardware errors (3.5%)
    - » 2 disk failures (0.5%)
  - isolated transients do not imply disk failures
  - but streams of transients indicate failing disks
    - » both Tertiary Disk failures showed this behavior

- **Transient error handling policy is critical in long-term availability of array**

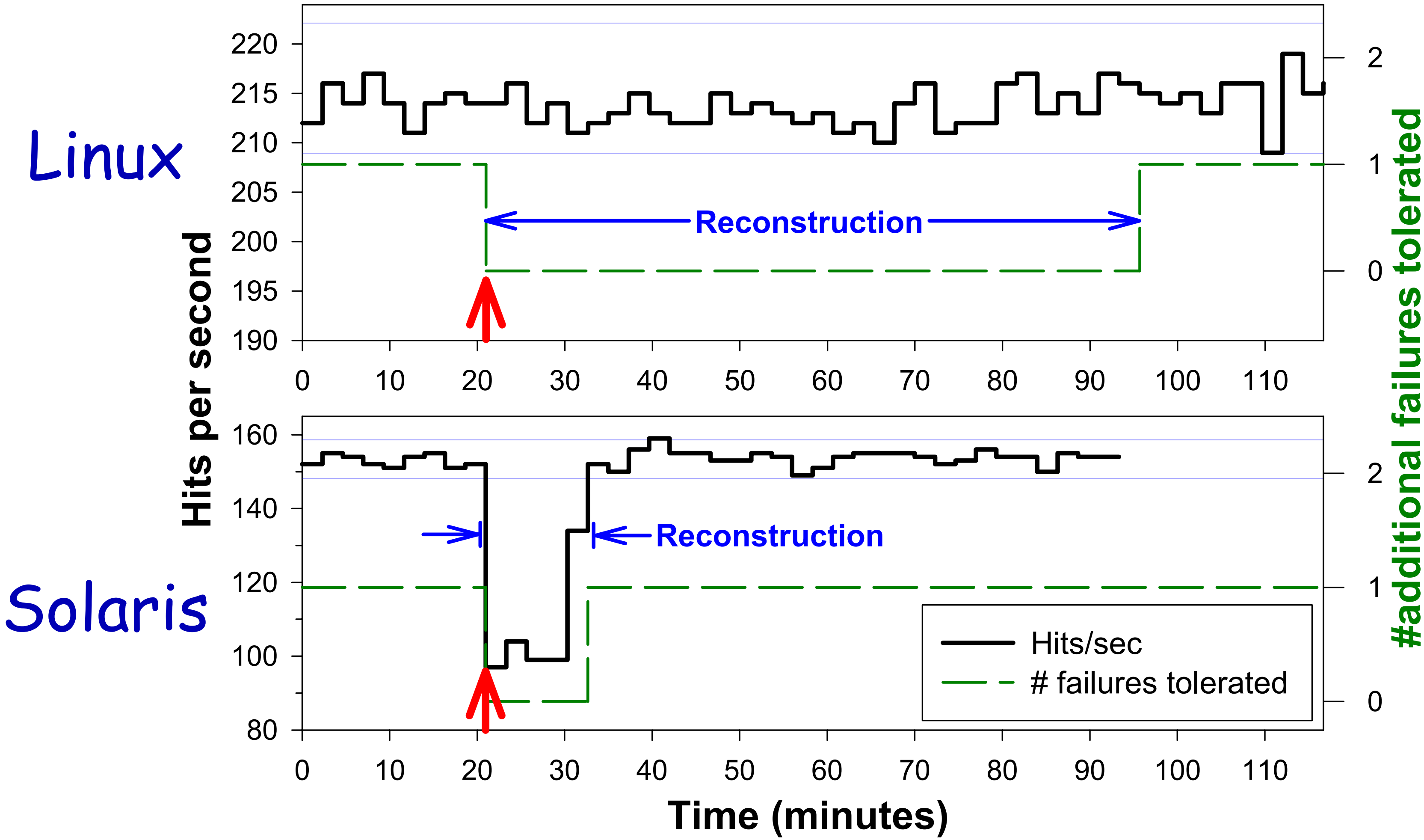
# Transient error handling (2)

- **Linux is *paranoid* with respect to transients**
  - stops using affected disk (and reconstructs) on *any* error, transient or not
    - » fragile: system is more vulnerable to multiple faults
    - » disk-inefficient: wastes two disks per transient
    - » but no chance of slowly-failing disk impacting perf.
- **Solaris and Windows are more forgiving**
  - both ignore most benign/transient faults
    - » robust: less likely to lose data, more disk-efficient
    - » less likely to catch slowly-failing disks and remove them
- **Neither policy is ideal!**
  - need a hybrid that detects streams of transients

# Reconstruction policy

- **Reconstruction policy involves an availability tradeoff between performance & redundancy**
  - until reconstruction completes, array is vulnerable to second fault
  - disk and CPU bandwidth dedicated to reconstruction is not available to application
    - » but reconstruction bandwidth determines reconstruction speed
  - policy must trade off *performance availability* and *potential data availability*

# Reconstruction policy: graphical view




- Visually compare Linux and Solaris reconstruction policies
  - clear differences in reconstruction time and perf. impact

# Reconstruction policy (2)

- **Linux:** favors performance over data availability
  - automatically-initiated reconstruction, idle bandwidth
  - virtually no performance impact on application
  - very long window of vulnerability (>1hr for 3GB RAID)
- **Solaris:** favors data availability over app. perf.
  - automatically-initiated reconstruction at high BW
  - as much as 34% drop in application performance
  - short window of vulnerability (10 minutes for 3GB)
- **Windows:** favors neither!
  - *manually-initiated* reconstruction at moderate BW
  - as much as 18% app. performance drop
  - somewhat short window of vulnerability (23 min/3GB)

# Double-fault handling

- **A double fault results in unrecoverable loss of some data on the RAID volume**
- **Linux:** blocked access to volume
- **Windows:** blocked access to volume
- **Solaris:** silently continued using volume, delivering *fabricated* data to application!
  - clear violation of RAID availability semantics
  - resulted in corrupted file system and garbage data at the application level
  - this *undocumented* policy has serious availability implications for applications

# Availability Conclusions: Case study

- **RAID vendors should expose and document policies affecting availability**
  - ideally should be user-adjustable
- **Availability benchmarks can provide valuable insight into availability behavior of systems**
  - reveal undocumented availability policies
  - illustrate impact of specific faults on system behavior
- **We believe our approach can be generalized well beyond RAID and storage systems**
  - the RAID case study is based on a general methodology

# Conclusions: Availability benchmarks

- **Our methodology is best for *understanding* the availability behavior of a system**
  - extensions are needed to distill results for automated system comparison
- ***A good fault-injection environment is critical***
  - need realistic, reproducible, controlled faults
  - system designers should consider building in hooks for fault-injection and availability testing
- **Measuring and understanding availability will be crucial in building systems that meet the needs of modern server applications**
  - our benchmarking methodology is just the first step towards this important goal

# Availability: Future opportunities

- **Understanding availability of more complex systems**
  - availability benchmarks for databases
    - » inject faults during TPC benchmarking runs
    - » how well do DB integrity techniques (transactions, logging, replication) mask failures?
    - » how is performance affected by faults?
  - availability benchmarks for distributed applications
    - » discover error propagation paths
    - » characterize behavior under partial failure
- **Designing systems with built-in support for availability testing**
- **Have ideas? You can help!**

# Part II

## Maintainability Benchmarks

# Outline: Maintainability Benchmarks

- **Motivation:** why benchmark maintainability?
- **Maintainability benchmarks:** an idea for a general approach
- **Case study:** maintainability of software RAID
  - Linux (RH6.0), Solaris (x86), and Windows 2000
  - User trials with five subjects
- **Discussion**

# Motivation

- **Human behavior can be the determining factor in system availability and reliability**
  - high percentage of outages caused by human error
  - availability often affected by lack of maintenance, botched maintenance, poor configuration/tuning
  - we'd like to build "touch-free" self-maintaining systems
- **Again, no tools exist to provide insight into what makes a system more maintainable**
  - our availability benchmarks purposely excluded the human factor
  - benchmarks are a challenge due to human variability
  - metrics are even sketchier here than for availability

# Metrics & Approach

- **A system's overall maintainability cannot be *universally* characterized with a single number**
  - too much variation in capabilities, usage patterns, administrator demands and training, etc.

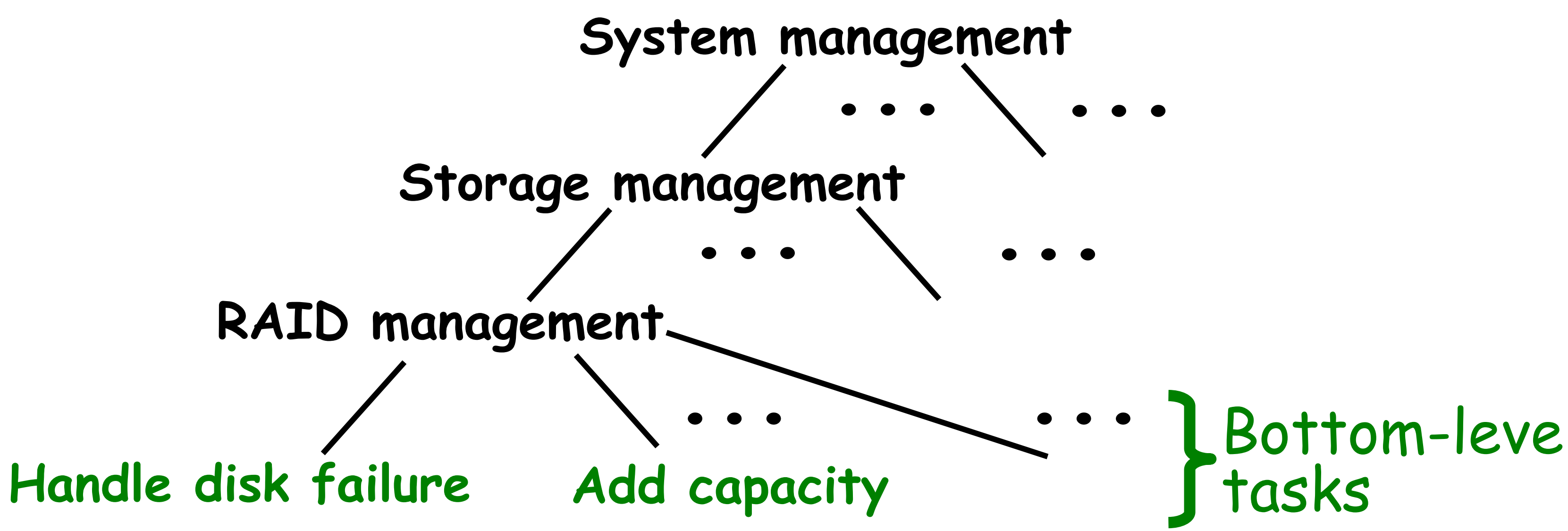
- **Alternate approach: *characterization vectors***
  - capture detailed, universal characterizations of systems and sites as vectors of costs and frequencies
  - provide the ability to distill the characterization vectors into site-specific metrics
  - can isolate human- and system-dependent factors

# Methodology

- **Characterization-vector-based approach**
  1) build an extensible taxonomy of maintenance tasks
  2) measure the normalized cost of each task on system
     » result is a cost vector characterizing components of a system's maintainability
  3) measure task frequencies for a specific site/system
     » result is a frequency vector characterizing a site/sys
  4) apply a site-specific cost function
     » distills cost and frequency characterization vectors
     » captures site-specific usage patterns, administrative policies, administrator priorities, . . .

# 1) Build a task taxonomy

- **Enumerate all possible administrative tasks**
  - structure into hierarchy with short, easy-to-measure bottom-level tasks
- **Example: a slice of the task taxonomy**



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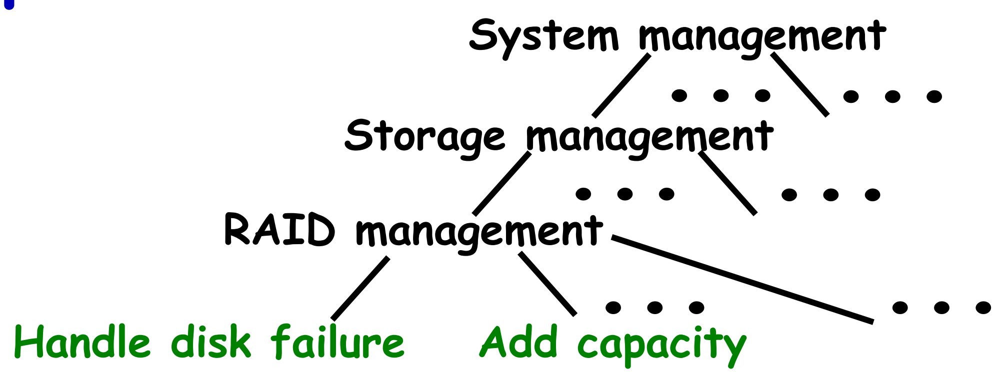



- **Sounds daunting! But...**
  - work by Anderson, others has already described much of the taxonomy
  - natural extensibility of vectors provides for incremental construction of taxonomy

# 2) Measure a task's cost

- **Multiple cost metrics**
  - **time**: how long does it take to perform the task?
    - » ideally, measure *minimum* time that user must spend
      - no "think time"
      - experienced user should achieve this minimum
    - » subtleties in handling periods where user waits for sys.
  - **impact**: how does the task affect system availability?
    - » use availability benchmarks, distilled into numbers
  - **learning curve**: how hard is it to reach min. time?
    - » this one's a challenge since it's user-dependent
    - » measure via user studies
      - how many errors do users make while learning tasks?
      - how long does it take for users to reach min. time?
      - does frequency of user errors decrease with time?

# 3) Measure task frequencies

- **Goal: determine relative importance of tasks**
  - inherently site- and system-specific
- **Measurement options**
  - administrator surveys
  - logs (machine-generated and human-generated)
- **Challenges**
  - how to separate site and system effects?
    - » probably not possible
  - how to measure frequencies on non-deployed system? on non-production site?
    - » estimates plus incremental refinement

# 4) Apply a cost function

- **Simple approach:**
  - **human time cost:** take dot product of time characterization vector with frequency vector
  - **availability cost:** take dot product of impact vector with frequency vector
  - *doesn't take learning curve into account*
- **Better approach:**
  - adjust time and availability costs using learning curve
    - » task frequency picks a point on learning curve
    - » task time and error rate adjust time and impact costs
  - then apply simple dot product
- **Sites can define any arbitrary cost function**

# Case Study

- **Goal is to gain experience with a small piece of the problem**
  - can we measure the time and learning-curve costs for one task?
  - how confounding is human variability?
  - what's needed to set up experiments for human participants?
- **Task: handling disk failure in RAID system**
  - includes detection and repair

# Experimental platform

- **5-disk software RAID backing web server**
  - all disks emulated (50 MB each)
  - 4 data disks, one spare
  - emulator modified to simulate disk insertion/removal
  - light web server workload
    - » non-overlapped static requests issued every 200us
- **Same test systems as availability case study**
  - Windows 2000/IIS, Linux/Apache, Solaris/Apache
- **Five test subjects**
  - 1 professor, 3 grad students, 1 sysadmin
  - each used all 3 systems (in random order)

# Experimental procedure

- **Training**
  - goal was to establish common knowledge base
  - subjects were given 7 slides explaining the task and general setup, and 5 slides on each system's details
    - » included step-by-step, illustrated instructions for task

# Experimental procedure (2)

- **Experiment**
  - an operating system was selected
  - users were given unlimited time for familiarization
  - for 45 minutes, the following steps were repeated:
    - » system selects random 1-5 minute delay
    - » at end of delay, system emulates disk failure
    - » user must notice and repair failure
      - includes replacing disks and initiating/waiting for reconstruction
  - the experiment was then repeated for the other two operating systems

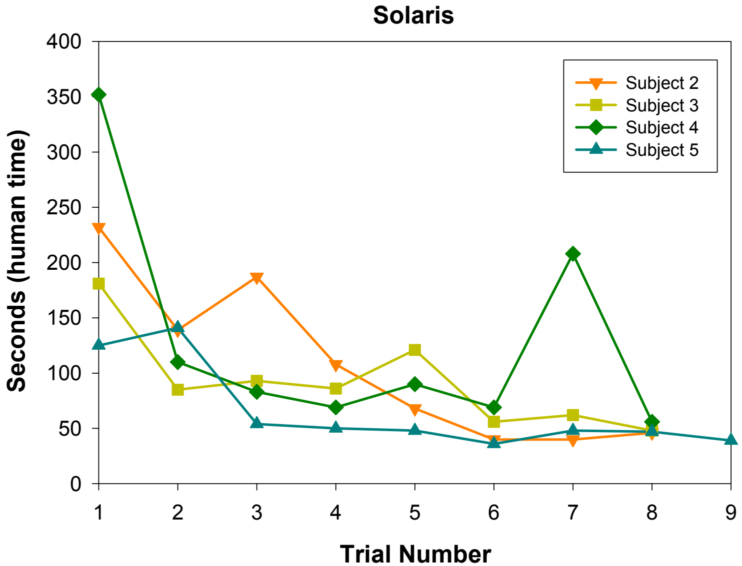
# Experimental procedure (3)

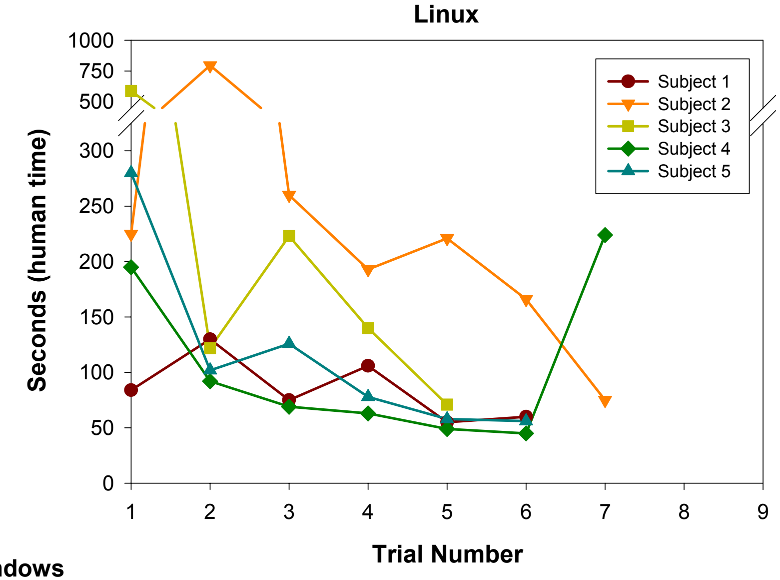
- **Observation**
  - users were videotaped
  - users used “control GUI” to simulate removing and inserting emulated disks

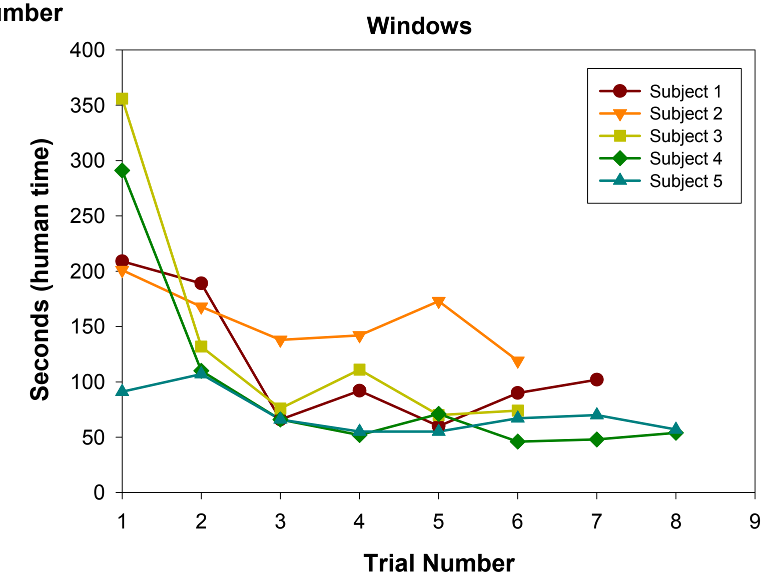

  - observer recorded time spent in various stages of each repair

# Sample results: time

- Graphs plot *human time*, excluding wait time



# Analysis of time results

- **Rapid convergence across all OSs/subjects**
  - despite high initial variability
  - final plateau defines "minimum" time for task
  - subject's experience/approach don't influence plateau
    - » similar plateaus for sysadmin and novice
    - » script users did about the same as manual users

# Analysis of time results (2)

- **Apparent differences in plateaus between OSs**

| Metric, in seconds | Solaris | Linux | Windows |
|---|---|---|---|
| Mean plateau value | 45.0 | 60.4 | 70.0 |
| Std. dev. | 8.9 | 12.4 | 28.7 |
| 95% conf. interval | 45.0 ± 12.3 | 60.4 ± 14.2 | 70.0 ± 33.0 |

- **But not statistically-supportable differences at 95% confidence**

| Claim | Supported at 95% confidence? | *P*-value | Subjects needed for 95% confidence |
|---|---|---|---|
| Solaris < Linux | No | 0.093 | 6 |
| Linux < Windows | No | 0.165 | 14 |
| Solaris < Windows | No | 0.118 | 7 |

  - we're not far off in size of study, though

# Learning curve results

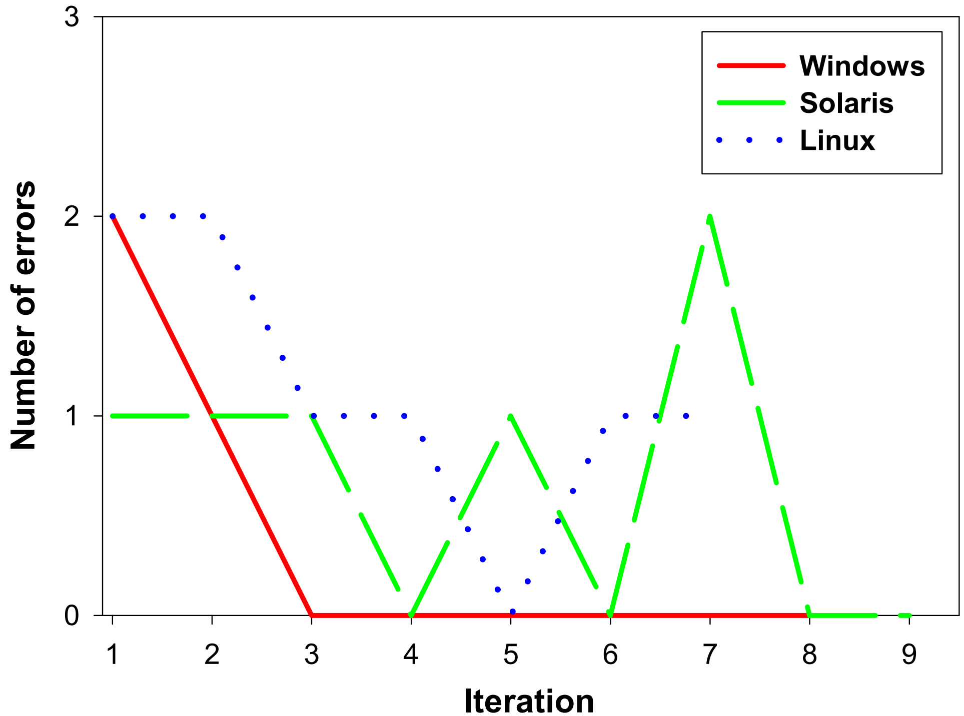
- **We measured the number of errors users made and the number of system anomalies**

| **Error type** | **Windows** | **Solaris** | **Linux** |
|---|---|---|---|
| Fatal Data Loss | 💣 | | 💣💣 |
| Unsuccessful Repair | | | 💣 |
| Fatal input inexplicably ignored | | | 💣 |
| User Error – Observer Required | 💣 | 💣💣 | 💣 |
| User Error – Recovered | 💣 | 💣💣💣💣 | 💣💣 |
| Large Software Anomaly | | | 💣💣 |
| Small Software Anomaly | | 💣 | |
| **Total number of trials** | **35** | **33** | **31** |

- Fewer errors for GUI system (Windows)
- Linux suffered due to drive naming complexity
- Solaris's CLI caused more (non-fatal) errors, but good design and clear prompts allowed users to recover

# Learning curve results (2)

- **Distribution of errors over time**




- **Only Windows shows expected learning curve**
  - suggests inherent complexity in Linux, Solaris that hurts maintainability?

# Summary of results

- **Time: Solaris wins**
  - followed by Linux, then Windows
  - important factors:
    - » clarity and scriptability of interface
    - » number of steps in repair procedure
    - » speed of CLI versus GUI
- **Learning curve: Windows wins**
  - followed by Solaris, then Linux
  - important factors:
    - » task guidance provided by GUI
    - » physically-relevant resource naming scheme
    - » clarity of status displays

# Discussion of methodology

- **Our experiments only looked at a small piece**
  - no task hierarchy, frequency measurement, cost fn
  - but still interesting results
    - » including different rankings on different metrics: OK!

- **Non-trivial to carry out full methodology**
  - single-task experiments took 1-2 man-weeks of work, with existing testbed
  - benchmarking an entire system will take lots of time, human subjects, new testbeds
  - methodology makes sense for a few important tasks, but needs to be constrained to become practical

# Making the methodology practical

- **The expensive part is what makes it work**
  - human subjects and experiments
- **Need an appropriate constrained environment**
  - high-end, where benchmark cost is justifiable
  - only well-trained administrators as subjects
    - » avoids learning curve complexity, simplifies expt's
  - pre-defined set of tasks
- **Target: TPC database benchmarks**
  - an optional "maintainability test" after regular run
  - vendor supplies *n* best administrators
  - use a combination of required tasks, fault injection
  - measure impact on perf., availability, human time

# Early reactions

- **Reviewer comments on early paper draft:**
  - "the work is fundamentally flawed by its lack of consideration of the basic rules of the statistical studies involving humans…meaningful studies contain hundreds if not thousands of subjects"
  - "The real problem is that, at least in the research community, manageability isn't valued, not that it isn't quantifiable"
- **We have an uphill battle**
  - to convince people that this topic is important
  - to make the benchmarks practical
  - to transplant understanding of human studies research to the systems community

# Looking for feedback...

- **Is manageability interesting enough for the community to care about it?**
  - ASPLOS reviewer: *The real problem is that, at least in the research community, manageability isn't valued*
- **Is the human-experiment approach viable?**
  - will the community embrace any approach involving human experiments?
  - is the cost of performing the benchmark greater than the value of its results?
  - *can we eventually get rid of the human?*
  - what are other possibilities?
- **What about unexpected non-repetitive tasks?**
  - like diagnosis

# Conclusions

- **Availability and maintainability benchmarks can reveal important system behavior**
  - **availability**: undocumented design decisions, policies that significantly affect availability
  - **maintainability**: influence of UI, resource naming on speed and robustness of maintenance tasks
- **Both areas are still immature compared to performance benchmarks**
  - lots of work needed to make the kind of results we demonstrated generally accessible
  - much future research in developing appropriate practical restrictions of our methodologies

# Discussion topics?

- **Extending benchmarks to non-storage domains**
  - fault injection beyond disks
- **Practical implementation**
  - testbeds: fault injection, workload, sensors
  - distilled numerical results
- **Issues of coverage and relevance**
  - again, fault injection
  - maintainability: capturing diagnosis tasks?

# Backup Slides

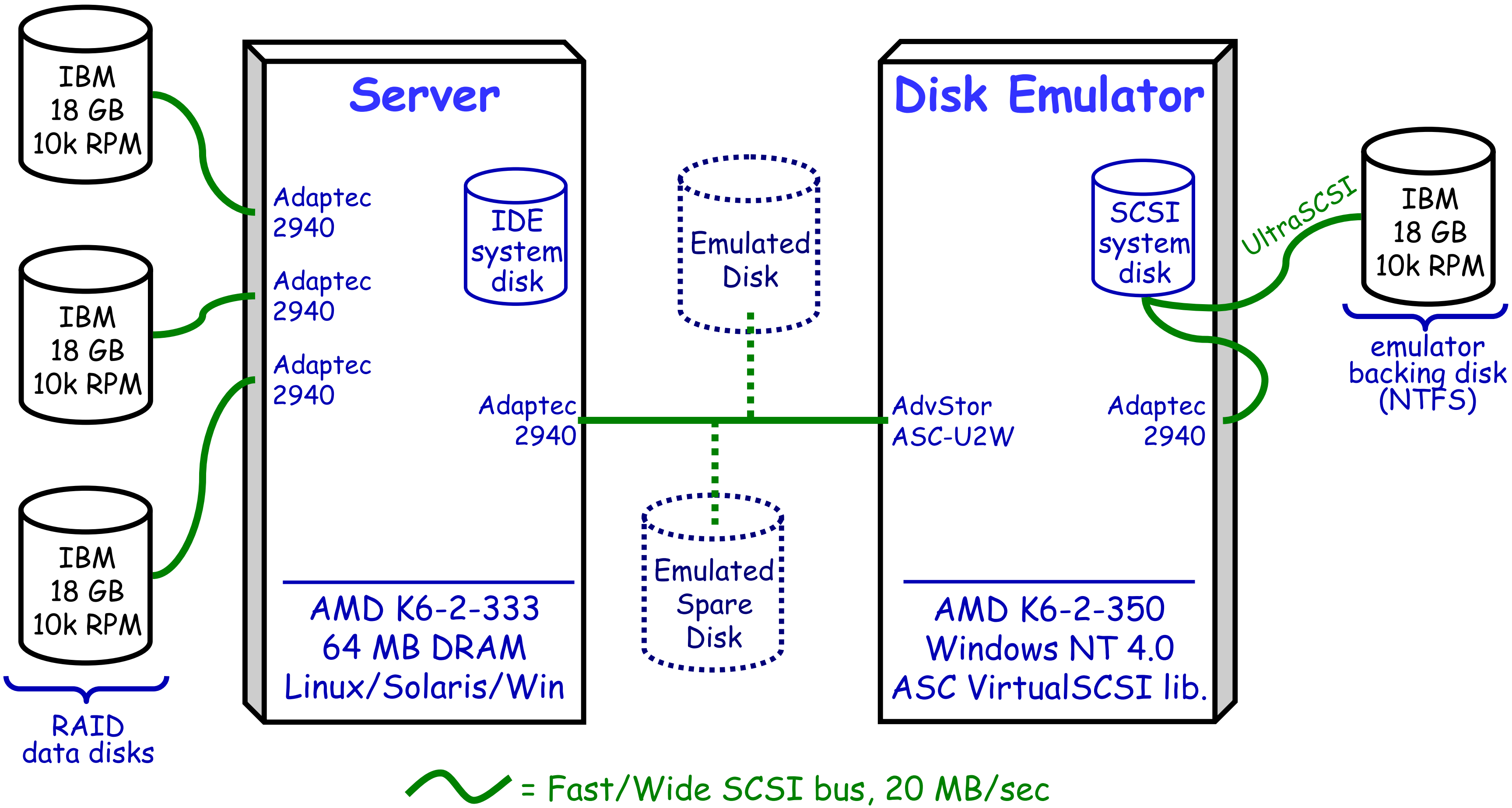
# Approaching availability benchmarks

- **Goal:** *measure* and *understand* availability
  - find answers to questions like:
    - » what factors affect the quality of service delivered by the system?
    - » by how much and for how long?
    - » how well can systems survive typical fault scenarios?
- **Need:**
  - metrics
  - measurement methodology
  - techniques to report/compare results

# Example Quality of Service metrics

- **Performance**
  - *e.g.*, user-perceived latency, server throughput
- **Degree of fault-tolerance**
- **Completeness**
  - *e.g.*, how much of relevant data is used to answer query
- **Accuracy**
  - *e.g.*, of a computation or decoding/encoding process
- **Capacity**
  - *e.g.*, admission control limits, access to non-essential services

# System configuration

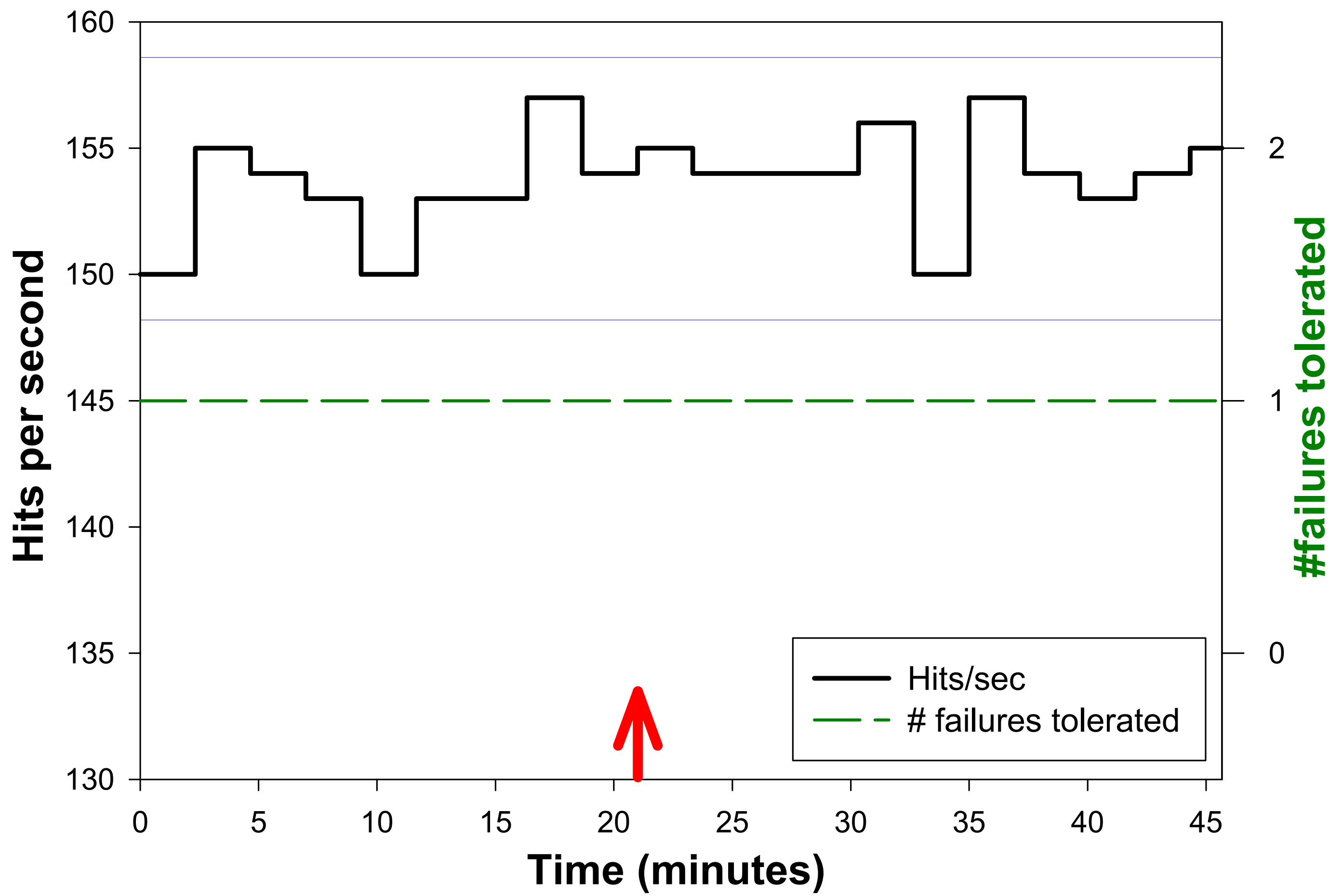



- RAID-5 Volume: 3GB capacity, 1GB used per disk
  - 3 physical disks, 1 emulated disk, 1 emulated spare disk
- 2 web clients connected via 100Mb switched Ethernet

# Single-fault results

- Only five distinct behaviors were observed

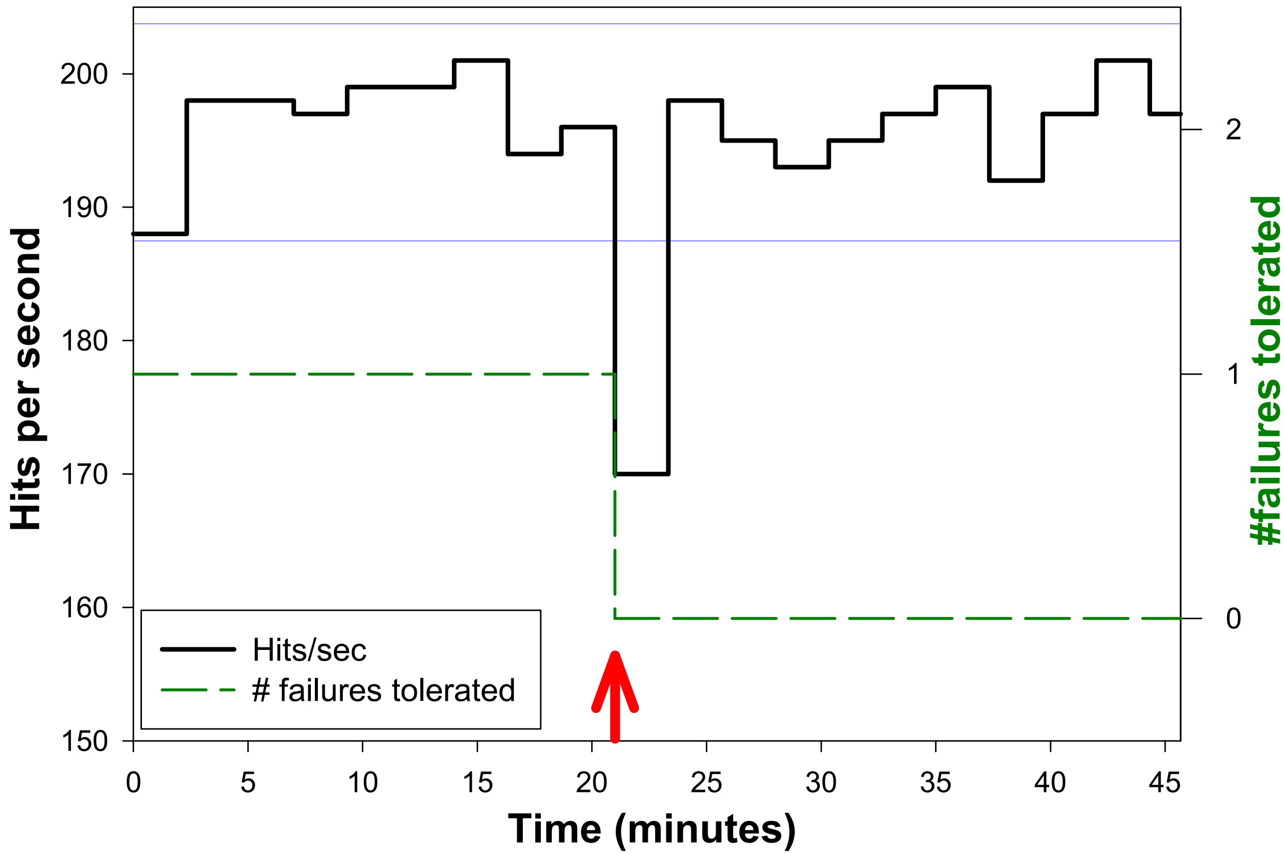
# Behavior A: no effect




- **Injected fault has no effect on RAID system**

Solaris, transient correctable read

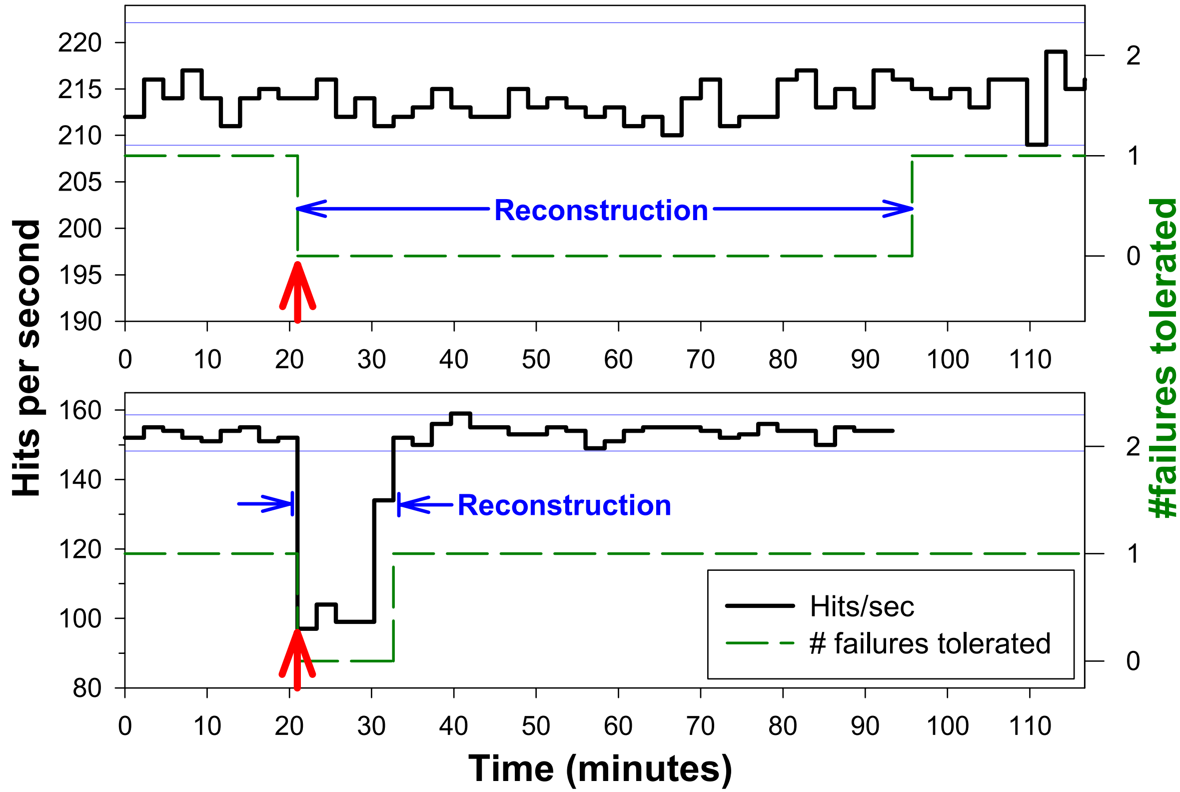
# Behavior B: lost redundancy




- **RAID system stops using affected disk**
  - no more redundancy, no automatic reconstruction

Windows 2000, simulated disk power failure

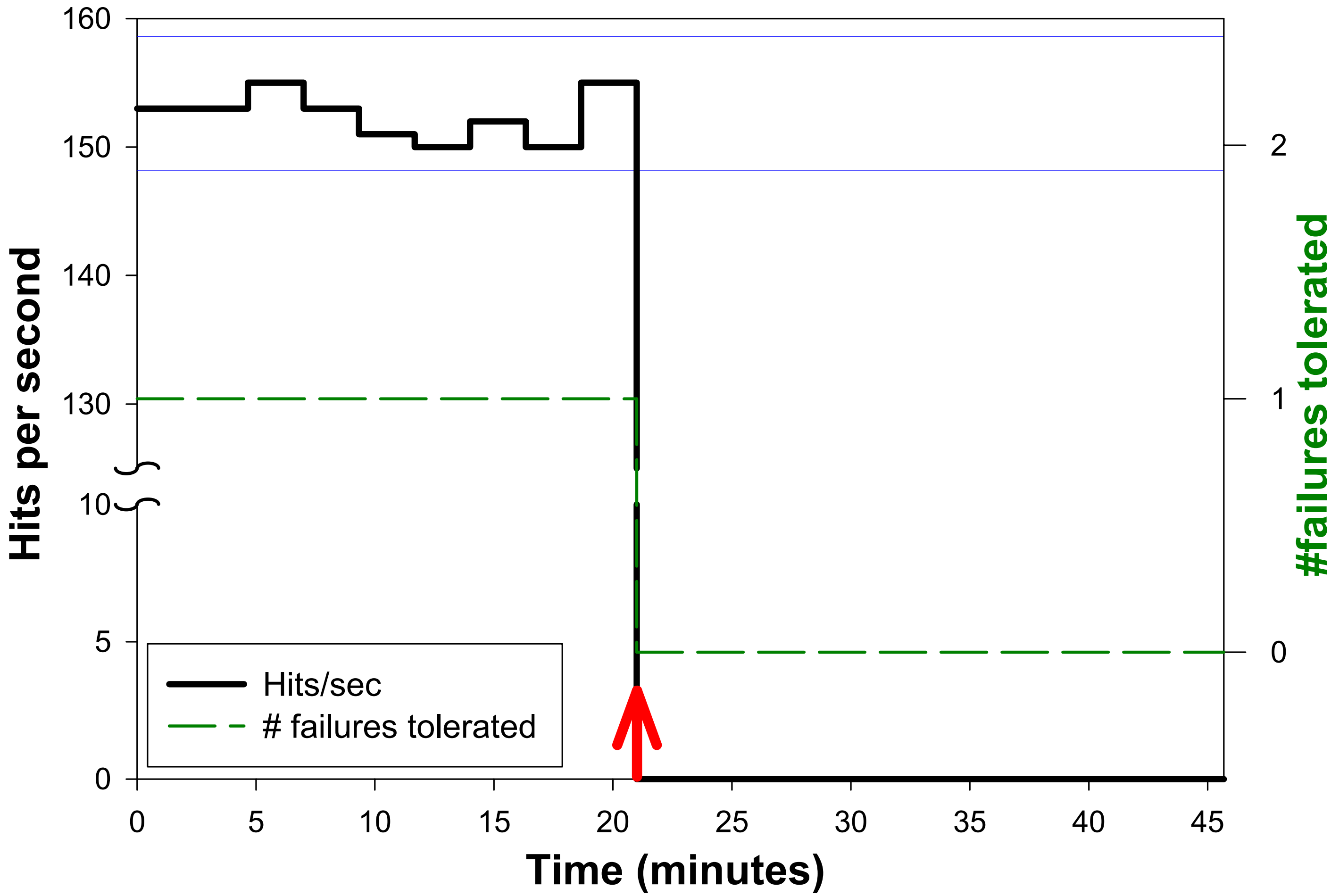
# Behavior C: automatic reconstruction




- **RAID stops using affected disk, automatically reconstructs onto spare**
  - C-1: slow reconstruction with low impact on workload
  - C-2: fast reconstruction with high impact on workload

C1: Linux, tr. corr. read; C2: Solaris, sticky uncorr. write

# Behavior D: system failure




- **RAID system cannot tolerate injected fault**

Solaris, disk hang on read

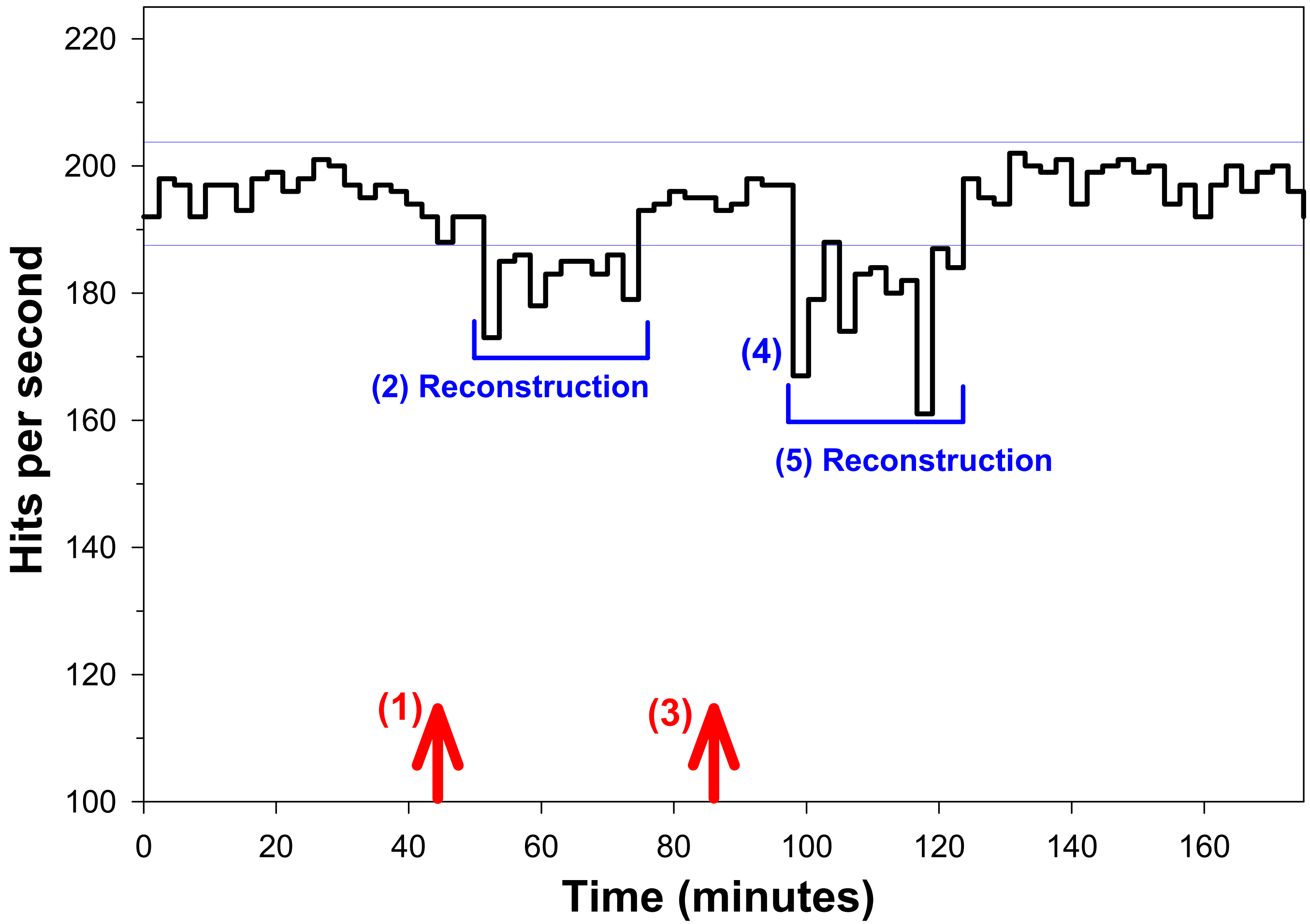
# System comparison: single-fault

| Fault Type | Linux | Solaris | Win2000 |
|---|---|---|---|
| Correctable read, T | reconstruct | no effect | no effect |
| Correctable read, S | reconstruct | no effect | no effect |
| Uncorr. read, T | reconstruct | no effect | no effect |
| Uncorr. read, S | reconstruct | reconstr. | degraded |
| Corr. write, T | reconstruct | no effect | no effect |
| Corr. write, S | reconstruct | no effect | no effect |
| Uncorr. write, T | reconstruct | no effect | degraded |
| Uncorr. write, S | reconstruct | reconstr. | degraded |
| Hardware err, T | reconstruct | no effect | no effect |
| Illegal command, T | reconstruct | reconstr. | no effect |
| Disk hang, read | failure | failure | failure |
| Disk hang, write | failure | failure | failure |
| Disk hang, nocmd | failure | failure | failure |
| Power failure | reconstruct | reconstr. | degraded |
| Pull active disk | reconstruct | reconstr. | degraded |

T = transient fault, S = sticky fault

- Linux reconstructs on *all* faults
- Solaris ignores benign faults but rebuilds on serious faults
- Windows ignores benign faults
- Windows can't automatically rebuild
- All systems fail when disk hangs

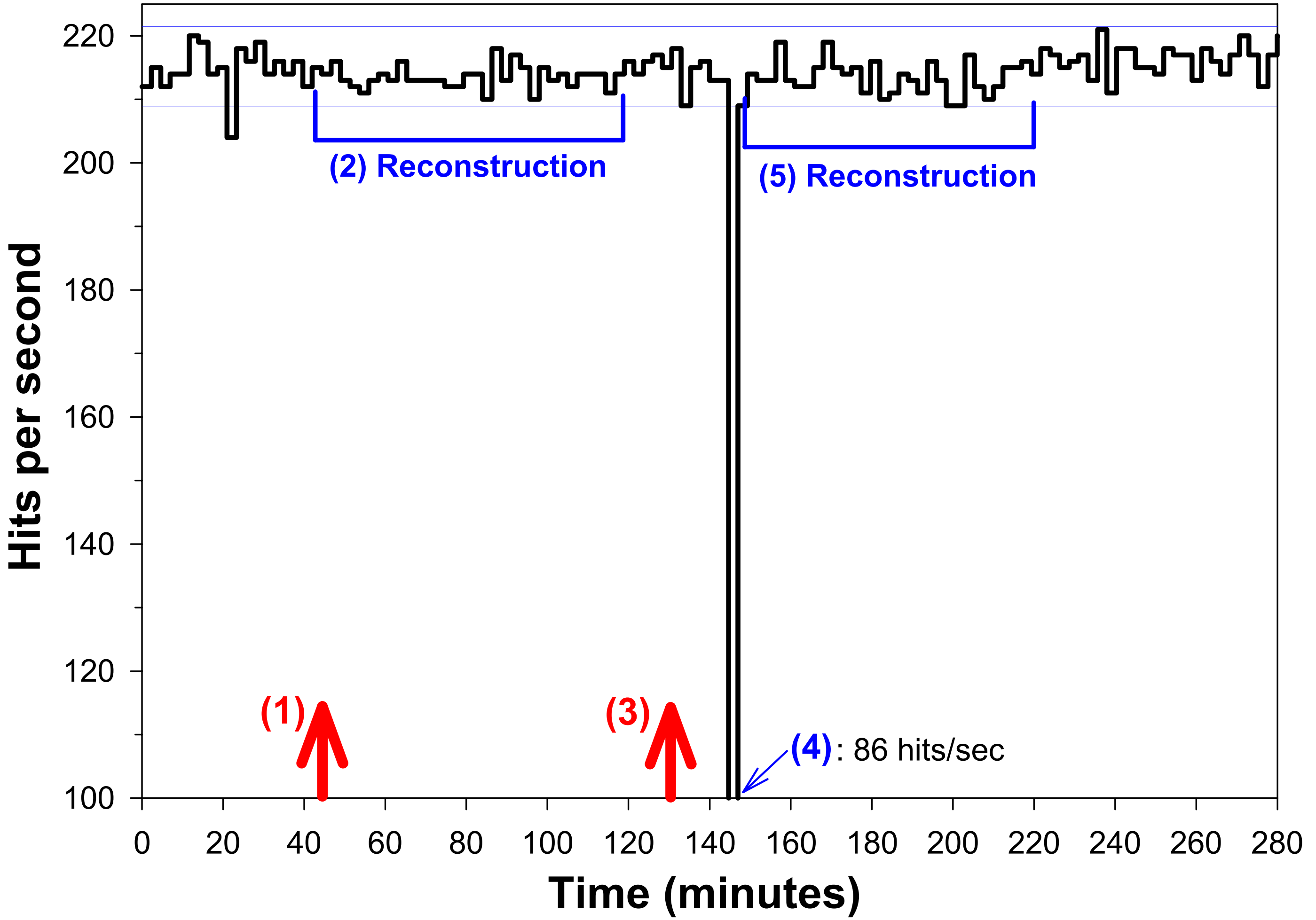
# Example multiple-fault result




- **Scenario 1, Windows 2000**
  - note that reconstruction was initiated manually

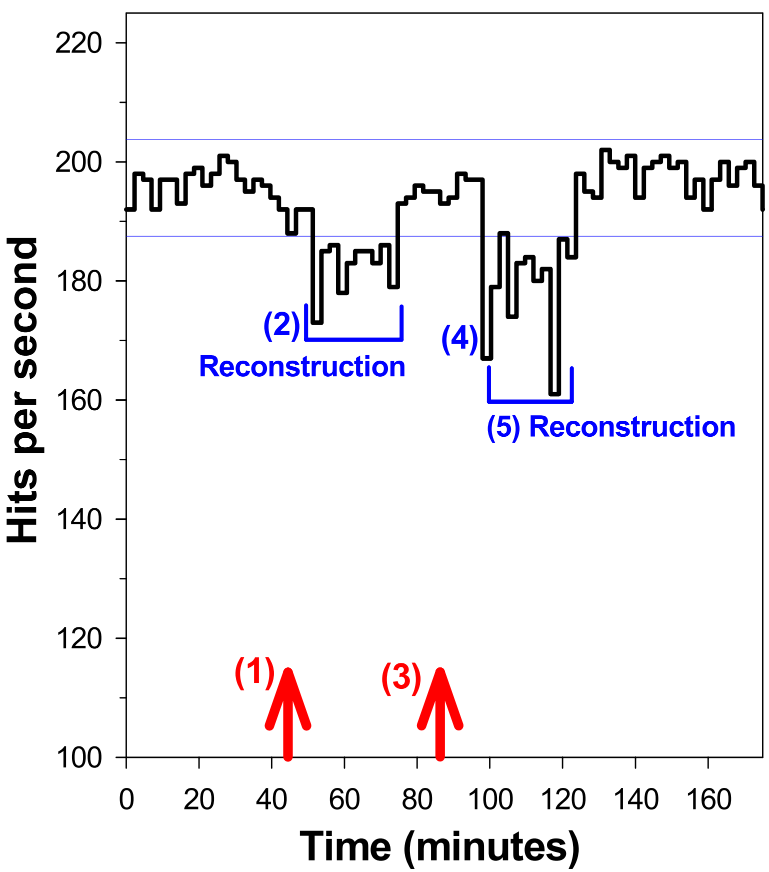
# Multi-fault results

- **Linux**

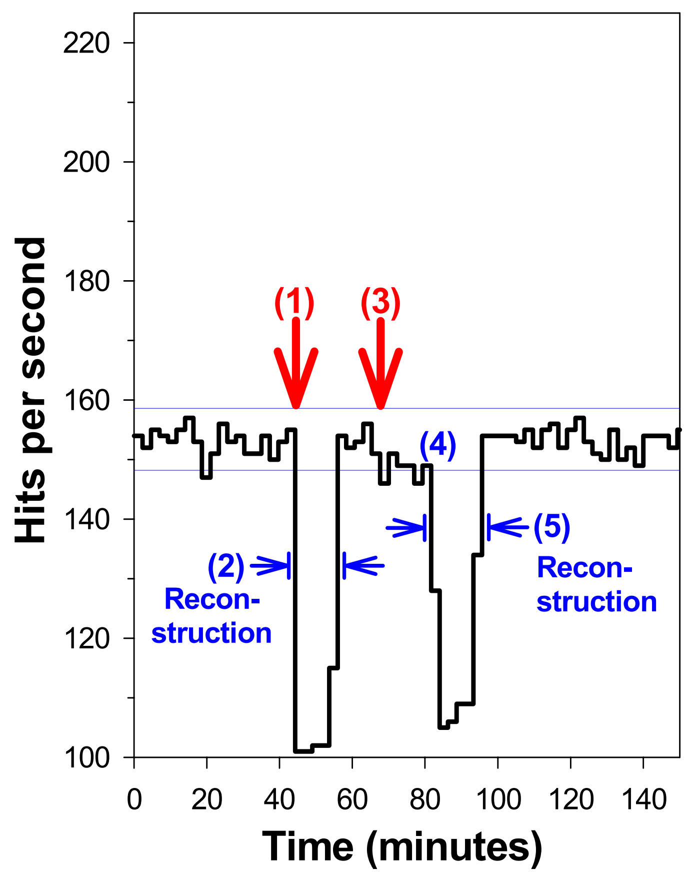


# Multi-fault results (2)

- **Windows 2000**




- **Solaris**



# Future Directions: Maintainability

- **We have a long way to go before these ideas form a workable benchmark**
  - completing a standard task taxonomy
  - automating and simplifying measurements of task cost
    - » built-in hooks for system-wide fault injection and user response monitoring
    - » can we eventually get the human out of the loop?
  - developing site profiling techniques to get task freqs
  - developing useful cost functions
- **Better human studies technology needed**
  - collaborate with UI or social science groups
  - larger-scale experiments for statistical significance
    - » collaborate with sysadmin training schools?