Storage Systems Management

Guillermo Alvarez, Kim Keeton, Arif Merchant, Erik Riedel, and John Wilkes

Hewlett-Packard Labs,
Storage Systems Program

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2000-06-SigmetricsTutorial

Tutorial overview

- **Introduction**
  - Why storage is important
  - Customer problems
  - Case study – DSS database server
  - The storage management market
- Storage Systems 101 – the building blocks
- Major problems in storage management
- Current solutions
- Our vision
- Research challenges
- Conclusions

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Introduction – why do we care?

- **Storage systems**
  - **the place where persistent data is kept**
  - the center of the universe!
- **Why?**
  - **information (and hence storage) is key to most endeavors**
  - **storage is big business (tens of $billion per year)**
  - **sheer quantities (hundreds of *petabytes* per year)**

  - ***"Storage will dominate our business in a few years"***
    - *Compaq VP, 1998*
  - ***"In 3 to 5 years, we will start seeing servers as peripherals to storage"***
    - *SUN Chief Technology Officer, 1998*
  - ***"We'll plug into whatever servers you have"***
    - *IBM Versatile Storage Server ad, 1999*

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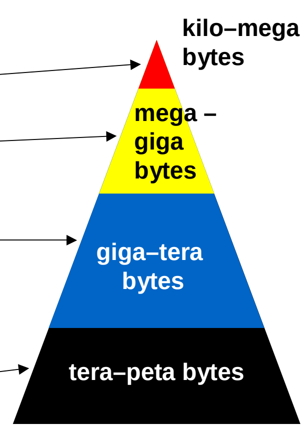
Introduction – storage hierarchy

- Primary storage: CPU
  - **registers** (1 cycle, a few ns)
  - **cache** (10-200+ cycles, 0.02–0.5us)
  - **local main memory** (0.2–4us)
  - **NUMA memory** (2–10x local memory)
- **Secondary storage (online storage)**
  - **magnetic disks** (2–20ms)
  - **solid state disks** (0.05–0.5ms)
  - **cache in storage controllers** (0.05–0.5ms)
- Tertiary storage
  - **removable media: tape cartridges, floppies, CD, …** (ms to minutes)
  - **tape libraries, optical jukeboxes (nearline)** (few s to few minutes)
  - **tape vaults** (few minutes to days)



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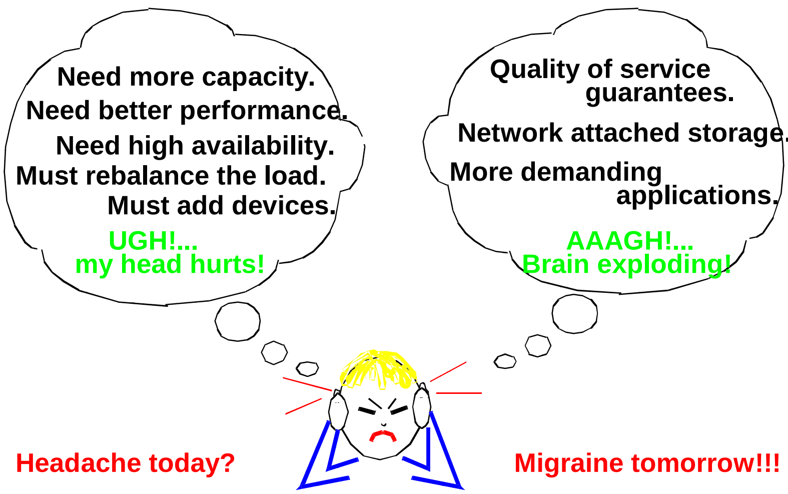
Customer problems – complexity



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Customer problems – scale

- **System scale is exploding**
  - Information density is dropping
    - text files >> DBMS >> data mining >> images >> email >> multimedia ...
  - Sheer numbers of applications, host systems, devices
  - Rate of growth
    - sometimes wildly unpredictable
- **Growing demands from business side**
  - continuous availability
  - predictable, stable performance
  - lower costs
- **Not enough skilled people**

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Customer problems – knobs

Too many knobs!

RAID 3 data layout, across 5 of the disks on array F, using a 64KB stripe size, 3MB dedicated buffer cache with 128KB sequential read-ahead buffer, delayed write-back with 1MB NVRAM buffer and max 10s residency time, dual 256KB/s links via host interfaces 12/4.3.0 and 16/0.4.3, 1Gb/s trunk links between FibreChannel switches A-3 and B-4, ...

- Business-critical availability
- 150 i/o per sec
- 200ms response time

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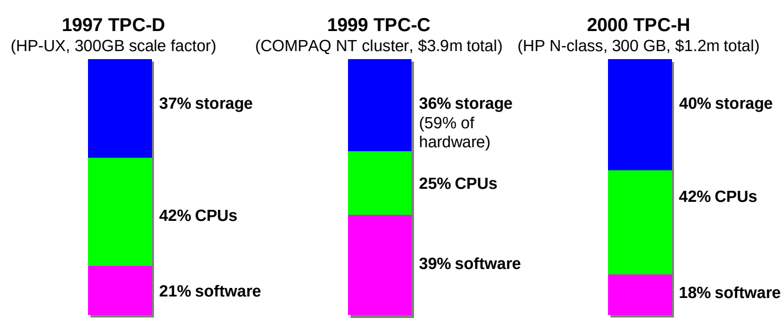
Customer problems – cost

- Storage is a big piece of the pie
  - 30-50% of total system cost in storage
  - And that's before you pay for management!

Normalized benchmark costs ($)



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Case study – DSS database server

- Hewlett-Packard N-class TPC-H Server
  - HP 9000 N4000 Enterprise Server
  - Informix Extended Parallel Server database
  - 8 x 550 MHz PA-RISC processors
  - 32 GB memory
  - 3 SureStore E Disk Array FC60s
    - 28 x 18.2 GB disks each in RAID1 (mirrored)
    - tables & indices
  - 4 SureStore E Disk System SC10s
    - 9 x 18.2 GB disks each in RAID0 (JBOD)
    - temporary space
  - 2.1 TB total storage (111 disks)
  - $1,154,133 total cost, $457,984 storage cost
  - 1,592 QphH@300GB, $973 / QphH@300GB

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Storage management market (DataQuest)

- Storage infrastructure
  - basic data organization
  - file systems, volume mgmt, physical replication
  - *who: various OS file systems (everyone does it), Veritas*
- Data management
  - backup, restore, archive, HSM
  - *who: Legato, IBM ADSM/Tivoli™, HP, CA Unicenter™, EMC, Sun*
- Enterprise storage management
  - everything else
  - "management of various storage resources on the network including [disk, tape]…"
  - *who: IBM/Tivoli™, HP SureStore™, Compaq SANworks™, CA Unicenter™, HighGround, BMC, CommVault*

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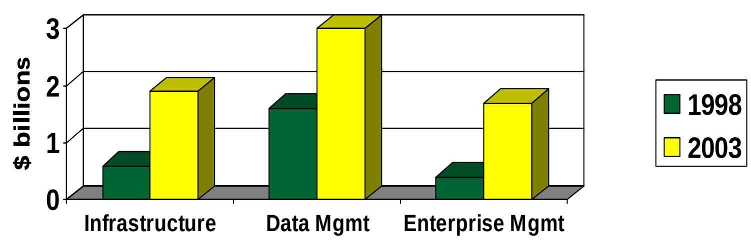
Market trends – storage management

- Total market
  - $2.6 billion in 1998, $6.6 billion by 2003
- Three areas
  - storage infrastructure
  - data management
  - enterprise storage resource management



Source: Dataquest, July 1999

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Outline

- Introduction
- Storage Systems 101 – the building blocks
  - Disk drives
  - Disk arrays
  - Storage area networks (SANs)
  - Network-attached storage (NAS)
- Major problems in storage management
- Current solutions
- Our vision
- Research challenges
- Conclusions

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Disk drive – what's inside?

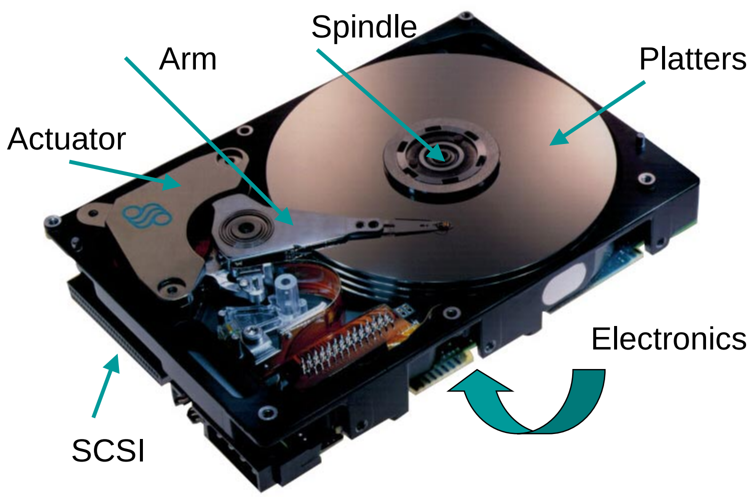

Image courtesy of Seagate Technology, Inc.

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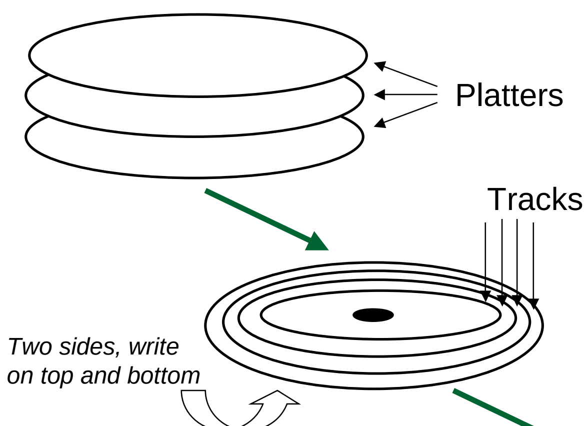
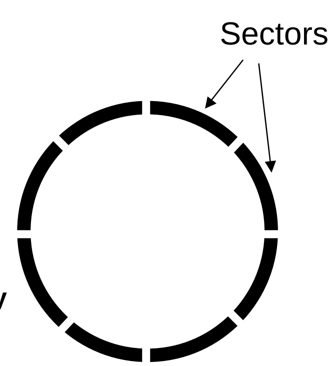
Disk drive – platters



- **1 to 12 platters per disk**
- **2 heads per platter**
- **2,000 to 40,000 tracks per platter**
- **50 to 200 kilobytes per track**
- **512 bytes per sector**



***Areal density* = linear density * track density**

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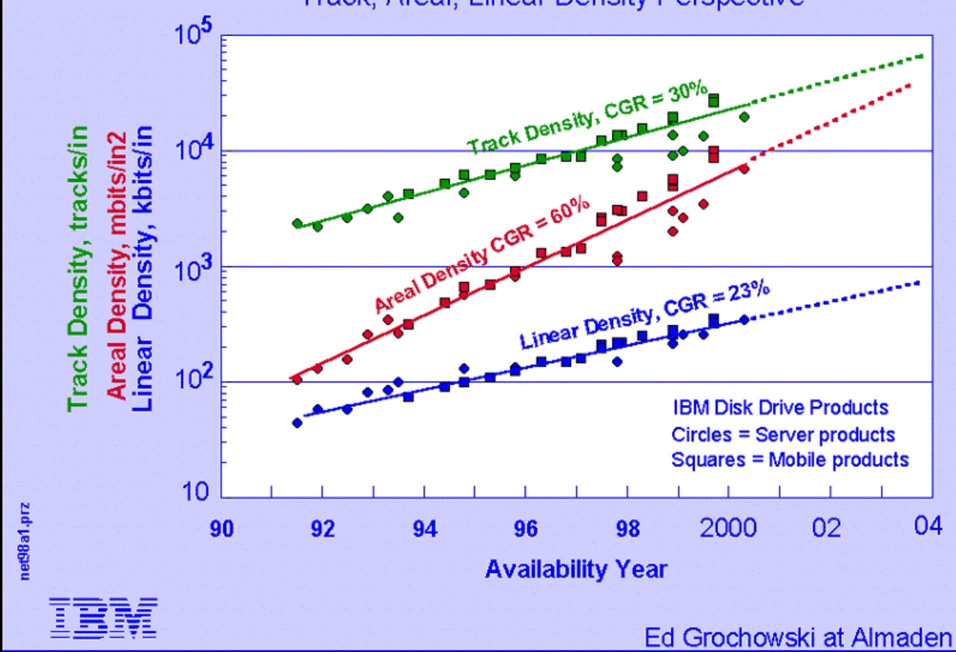
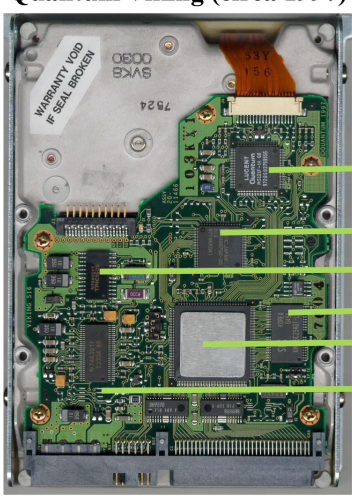
Trends



Disk drive – electronics

Quantum Viking (circa 1997)



6 Chips

R/W Channel	♦ **Connect to disk**
uProcessor 32-bit, 25 MHz	♦ **Control processor**
Power Array	
2 MB DRAM	♦ **Cache memory**
Control ASIC SCSI, servo, ECC	♦ **Control ASIC**
Motor/Spindle	♦ **Connect to motor**

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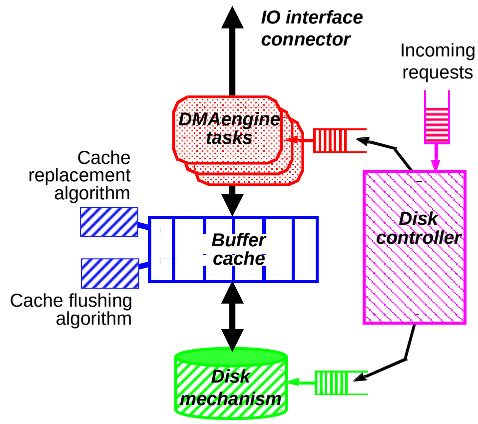
Disk drive – on-disk controller

- **Caching**
  - read-ahead
  - write behind (careful!)
  - atomicity guarantees (not!)
- **Controlling the mechanism**
  - head scheduling
  - spindle motor
  - servo tracking
- **Data path management**
  - protocol sequencing
  - request scheduling



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Why disk arrays?

Because disks are slow.

AND

Because *stuff* happens.

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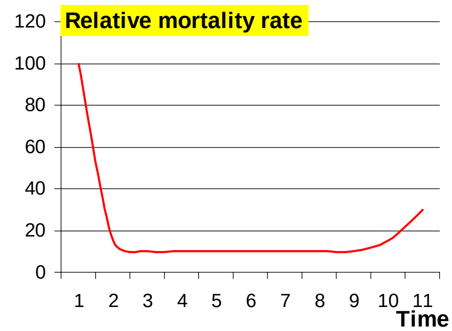
Problem – failures happen

- **Things break -- in a moderately predictable way in aggregate**



- **Metrics:**
  - **MTTF: mean time to failure –** *a rate, not a period*
  - **AFR: annual failure rate (better – but still just middle of "bathtub")**
  - **MTTR: mean time to repair**

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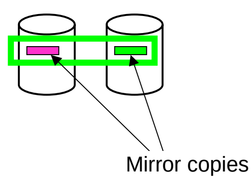
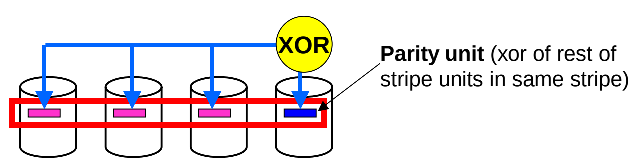
Solution – redundancy

- **Complete copies**
  - **replication, *mirroring***



- **Partial redundancy**
  - **Hamming codes/ECC**
    - **tolerates mangling of elements**
    - **unnecessarily strong – we know when disks are broken**



  - **Parity**
    - **XOR sets (stripes) of data blocks to calculate a *parity block***
    - **any data block can be reconstructed from the others + parity**

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How redundancy helps

- Individual disk drives
  - originally (mid-1980s), these were among the most unreliable components in a system
  - nowadays, they are one of the more reliable ones (AFR of 1 to 2%)
  - but failure rates are proportional to numbers …
- Assumes independent failures
  warning! danger! caution! error!
- With no redundancy …
  AFR_{disks} ~= N_{disks} * AFR_{disk}
- With one degree of redundancy …
  AFR_{raid} ~= $AFR_{disks}(N_{disks})$ * $MTTR_{disk}$ * $AFR_{disks}(N_{disks}-1)$

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Downsides of redundancy

- Cost
  - replicating everything costs 2x as much storage
  - solution – partial redundancy
- Slower updates
  - 2x as many copies to write to
  - … even worse with partial redundancy
- Greater complexity
  - 80 - 90% of disk array firmware is error handling
  - lots and lots of configuration choices …

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Disk array taxonomy

RAID = Redundant Arrays of Inexpensive Disks

Currently accepted RAID levels:

- **0: no redundancy (JBOD)**
- **1: full copy (mirroring)**
- **10: striped mirrors**
- 2: Hamming-code/ECC (not used)
- 3: byte-interleaved parity
- 4: block-interleaved parity (more useful variant of RAID3)
- **5: rotated block-interleaved parity**
- 6: double parity ("P+Q parity" -- rare)

Note: **not really levels, just a list**

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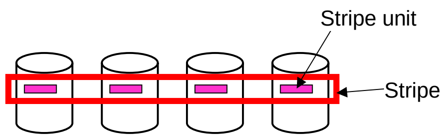
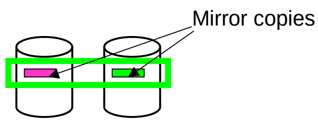
RAID levels 0, 1, 10

- **RAID0: striping (**no redundancy**)**



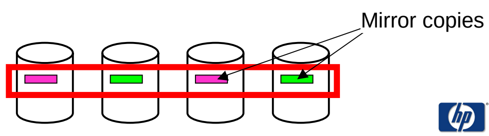
Striping **balances the load and allows large transfers to happen in parallel**

- **RAID1: aka mirroring (**full redundancy**)**



Mirroring **gives 2x the read bandwidth per disk, but writes have to go to both**

- **RAID10: striped mirroring (**full redundancy**)**



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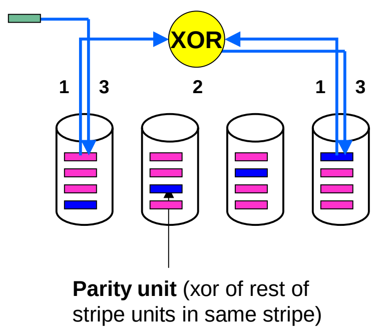
RAID level 5

- **RAID5 - rotated-parity striping to balance the load**
- **Updating parity is expensive for small writes**
  - **write-caching becomes especially important**



1. Read old data & parity
2. Compute new parity
3. Write new data + parity

=> 4x I/O operations per small write

Rotating the parity **balances the parity load across all the disks; striping allows fast large transfers**

RAID5 is the configuration of choice for all but performance-intensive workloads

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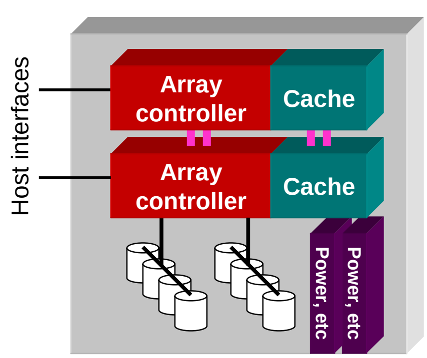
Disk array – mid-range architecture

- **Mid-range array** (e.g., HP FC60)
  - **sometimes separate controller and disk boxes**
  - **up to 1 to 2 TB disk, 0.5 GB cache memory**
  - **can saturate a 100 MB/s FibreChannel link; O(10,000 IOs/s)**



Packaging:
- whole array is in a single box, or
- array controller is in separate box

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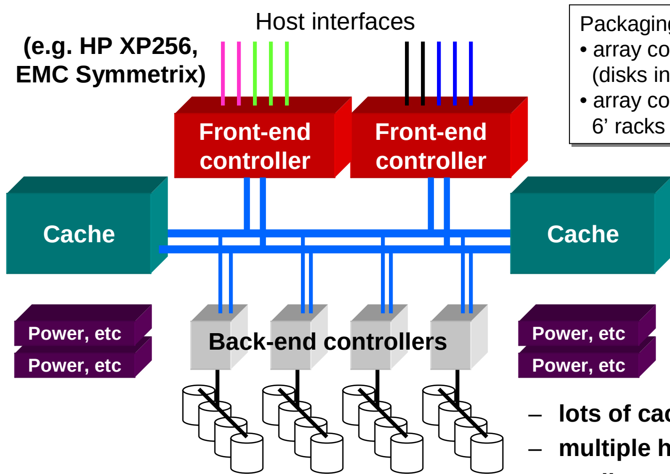
Disk array – high-end architecture



Packaging:
- array controller in a separate box (disks in rack-mountable trays), to
- array controller is one of several 6' racks

– up to a few TB disk, a few GB cache
– can saturate a few 100 MB/s FibreChannel links
– O(50,000+ IOs/s)
– lots of caching
– multiple host interfaces
– quality power, cabling, cooling
– phone-home, remote mgmt, support infrastructure

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Disk arrays – logical units

- **Arrays provide multiple LUNs (SCSI Logical UNits)**
  – basic unit of control, management
  – one or more disk drives bound together into a common layout (choose a RAID level)
  – different LUNs can have different sizes, different layouts
  – 8 to 32 LUNs at the mid-range
  – thousands of LUNs at the high-end
    - SCSI limit: 4096 LUNs, from a 12 bit LUN identifier
- **A few common variations (there are many more)**
  – parts of disks instead of whole disks
  – LUNs may be named relative to ports, not uniquely
  – LUNs can have different caching behavior

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Why storage networks?

Because we want to *share* storage?*

***Sharing isn't always easy.**

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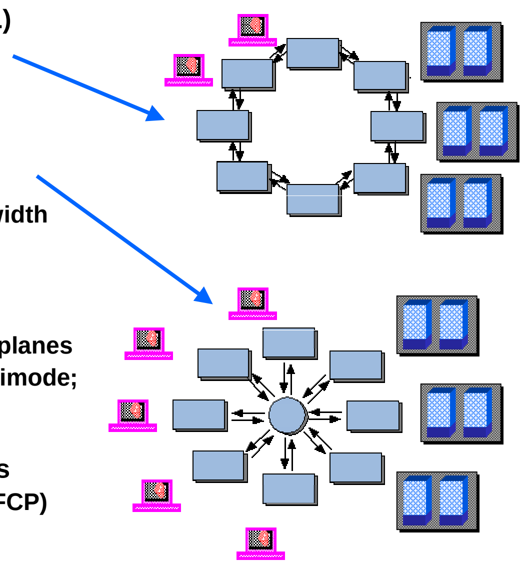
Storage Area Networks – FibreChannel

- **Arbitrated Loop (FC-AL)**
  - **shared, dual loop**
- **Switched Fabrics**
  - **dedicated ports**
    - **hosts, disks, arrays**
  - **high aggregate bandwidth**
- **Same Physical Layer**
  - **100 MB/s bandwidth**
  - **copper: coax, or backplanes**
  - **fibre: up to 500m multimode; 10km single-mode**
- **SCSI, IP encapsulations**
  - **FC Control Protocol (FCP)**
  - **SCSI over IP**



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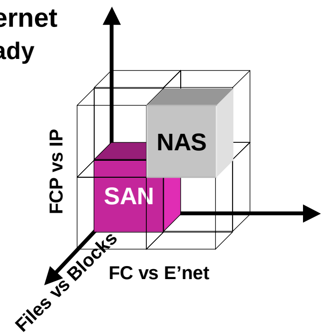
LAN vs SAN vs NAS?

- Network hardware: FibreChannel vs Ethernet
  - 1 Gb/s E'net available today, 2 Gb/s FC ready
  - 10 Gb/s E'net will (probably) be ready first
- Storage interface: blocks vs "files"
  - block storage devices (SCSI)
  - object-based storage (under discussion)
  - *NAS* => file servers (Netware, NFS, CIFS)
- Network protocol: FCP vs TCP/IP
  - specialized protocol vs. general-purpose one
- SAN (Storage Area Network)
  - dedicated network, used (largely) for storage
  - *whatever the protocol!*



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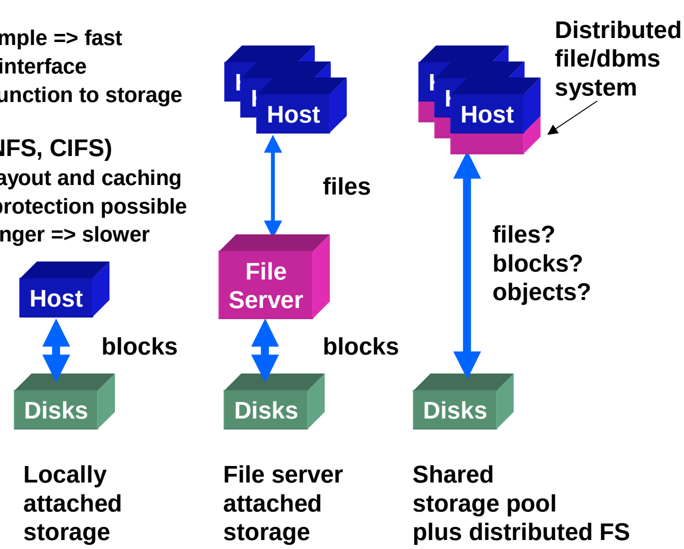
Open issue – blocks vs. files?

- Blocks (SCSI)
  - \+ critical path simple => fast
  - – very "simple" interface
  - – hard to push function to storage device
- Files (Netware, NFS, CIFS)
  - \+ can optimize layout and caching
  - \+ finer-grained protection possible
  - – critical path longer => slower



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Outline

- Introduction
- Storage Systems 101 – the building blocks
- Major problems in storage management
  - System design and configuration (device management)
  - Problem detection and diagnosis (error management)
  - Capacity planning (space management)
  - Performance tuning (performance management)
  - High availability (availability management)
  - Automation (self-managing storage)
- Current solutions
- Our vision
- Research challenges
- Conclusions

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System design and device configuration

- How to decide which storage devices to buy
  - how many?
  - what kind?
    - how fast, how big
  - how are they connected?
    - SCSI, FC-AL, switches, SAN, NAS
- How to set device configuration parameters
  - RAID level?
    - RAID0, RAID1, RAID10, RAID5
  - disks per stripe?
  - stripe size?
  - buffer management?
  - prefetch and writeback policies?
    - aggressive, conservative

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Problem detection and diagnosis

- What must be monitored to detect device failures?
  - across hosts, arrays, networks
  - across multiple vendors
  - across multiple operating systems
- What system information must be available to diagnose root cause?
  - isolate problems
- What capabilities must be available to correct problems?
  - redundancy (RAID levels)
  - multiple network paths
  - transparent failover
  - replacement parts (hot spares)

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Capacity planning

- How to keep up with users' capacity demands?
  - tracking growth
  - predicting growth
  - acquiring additional storage
  - installing and configuring additional storage
  - identifying hot vs. cold data
  - often tied closely to performance
  - variance in usage patterns

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Performance tuning

- How should the storage system be designed to maximize performance?
  - LUN design
  - logical volume design
  - file/database layout onto logical volumes
- What must be monitored to detect performance bottlenecks?
- How do we translate between different levels of abstraction?
  - LUNs vs. logical volumes vs. database table
  - blocks vs. files
- Service level agreements (SLA and QoS)
  - specify customer business requirements
  - "enforce" service levels

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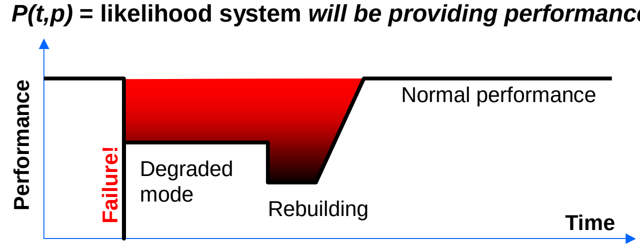
High availability

- What design must we use to avoid single points of failure?
- What RAID levels must be used to achieve desired availability?

- Reliability
  - *R(t)* = likelihood system *up continuously* from time 0 to time *t*
- Availability
  - *A(t)* = likelihood system *will be up* at time *t*
- Performability
  - *P(t,p)* = likelihood system *will be providing performance p* at time *t*



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Automation

- How do we make all this happen with minimal human involvement?
  - remove the human from the loop whenever possible
- High-level goals
  - what to do, not how to do it
  - set and forget
- Manipulate device knobs
- Automatic performance analysis
- Service level agreements
- Grow/shrink as necessary
  - capacity *and* performance
- Transparently

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Outline

- Introduction
- Storage Systems 101: the building blocks
- Major problems in storage management
- Current solutions
  - Storage management products
- Our vision
- Research challenges
- Conclusions

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Storage management products

- Pre-sales tools
  - system design and device configuration
  - capacity planning
  - high availability
- *IBM Tivoli™*
- *Compaq SANworks™*
- *HP SureStore™ SAN Manager*
- *CA Unicenter™*
  - problem detection and diagnosis
  - high availability
- *HighGround Storage Resource Manager™*
- *BMC Patrol™*
  - problem detection and diagnosis
  - performance monitoring

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Outline

- Introduction
- Storage Systems 101 – the building blocks
- Major problems in storage management
- Current solutions
- Our vision
  - Stress-free storage
  - The storage utility
- Research challenges
- Conclusions

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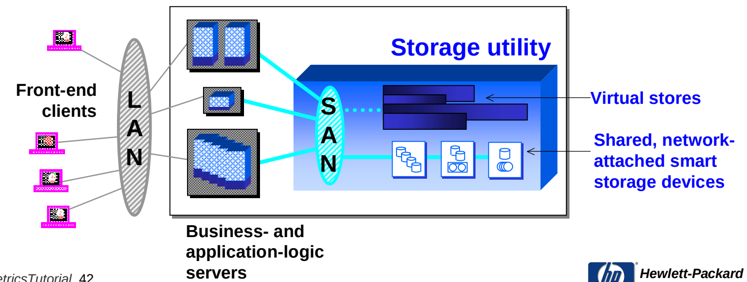
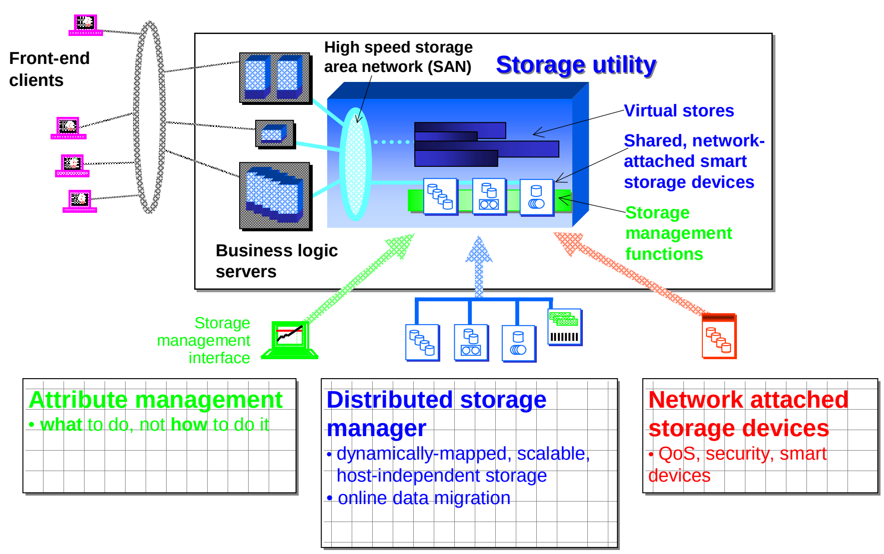
Stress-free storage

A storage system for the enterprise made from:

- **High-quality individual components**
- ***Management software* to glue it all together**
- **Result – easy-to-use, easy-to-manage system that delivers business goals**
  - **reduce personnel to a single person and a dog**
  - **have *complain* and *commend* buttons for each user**



The storage utility



The storage utility – how is it done?

Just a few Big Ideas ...

- **Goal-directed self-management**
  - specify what to do (goals), not how to do it (implementation)
- **Automatic (re)design and (re)configuration**
  - to reduce complexity & human effort
- **Predictable behavior through guarantees**
  - QoS = performance + availability + cost
- **Software as the key differentiator**

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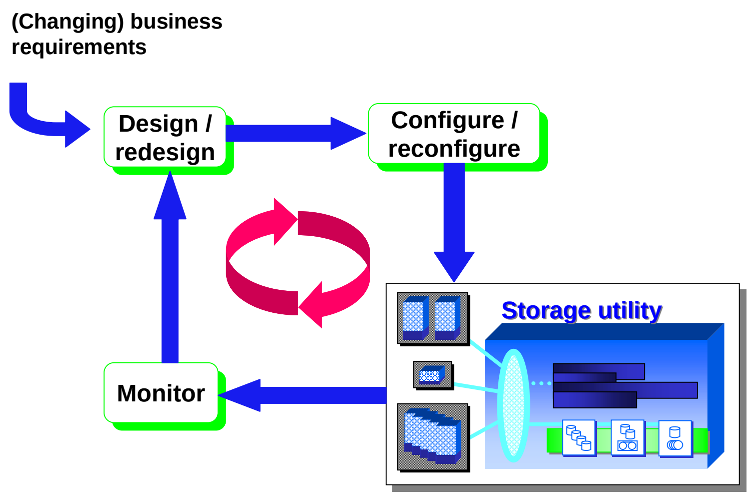
Customer lifecycle



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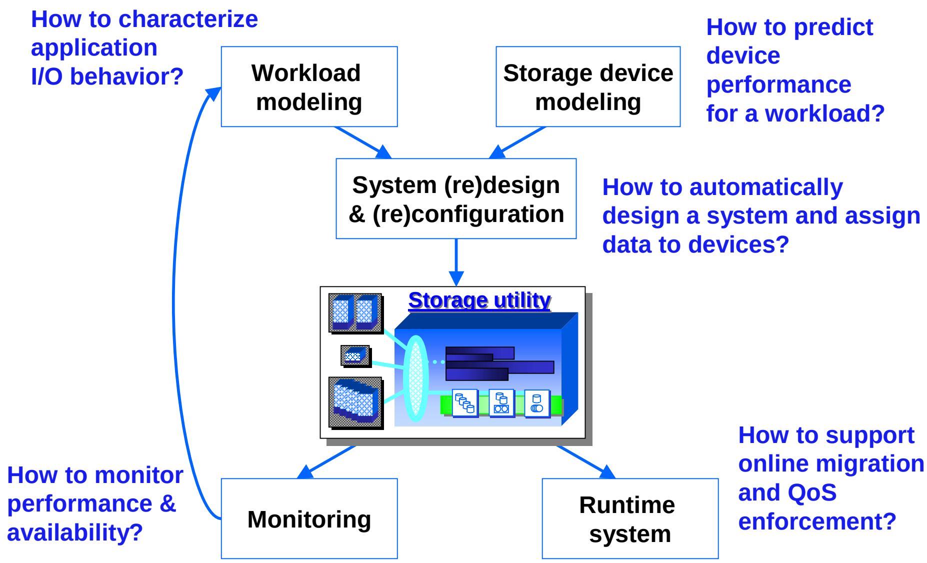
Research challenges from lifecycle



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Outline

- Introduction
- Storage Systems 101 – the building blocks
- Major problems in storage management
- Current solutions
- Our vision
- **Research challenges**
  - Workload modeling
  - Storage device modeling
  - Initial system design
  - System configuration
  - Online system monitoring
  - System reconfiguration
  - Some additional challenges
- Conclusions

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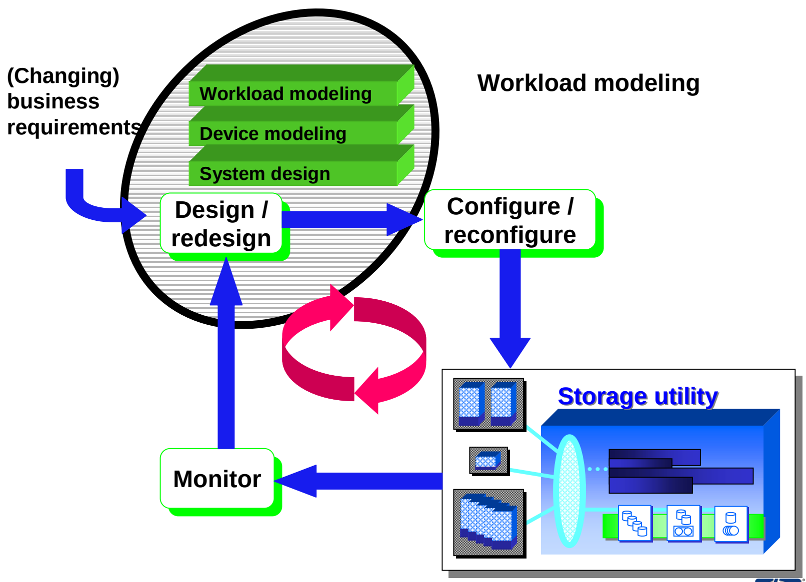
Customer lifecycle – the (re)design step



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Research challenge – workload modeling

Goal: succinctly capture important workload characteristics
- Requirements
  - capacity, availability
  - response time, b/w, I/O rate
- Behaviors (use patterns)
  - spatial locality (hot spots, reuse)
  - temporal locality (burstiness)
  - request size

♦ QoS, Service Level Agreements, or guarantees
- If application behaves *this way*, storage system will provide *this much* service.

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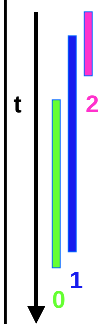
Workload modeling - SSP approach

- Declarative specification of workload attributes
- Workload = set of stores + streams
  - Stores capture static requirements (e.g., capacity)
  - Streams capture dynamic workload requirements (e.g., bandwidth, availability) to a store
- (Simplified) workload unit example:




```
Store store0 {  {capacity 1e9 (bytes)} }
Stream stream0 {
   {boundTo store0}
   {requestRate  {ARW 800 600 200}  (request/sec)}          requirements
   {requestSize  {ARW 4096 4096 4096}(bytes)}
   {sequentialRunCount {mean-variance 20 5} (requests)}  use patterns
   # phasing (correlation) behavior
   {onTime 90 (seconds)} {offTime 99 (seconds)}
   {overlapFraction { {stream1 1.0}
                      {stream2 0.0} }
}
```

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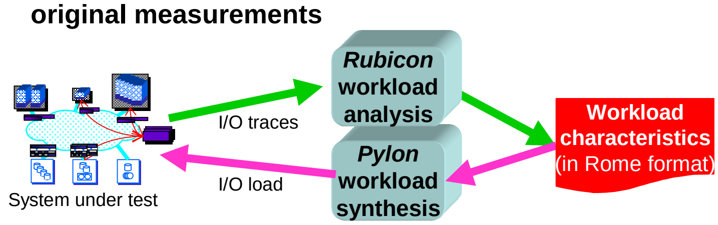
Workload modeling – Rubicon

- **Workload characterization**
  - evaluate requirements and behaviors of applications
- **Device characterization**
  - measure device performance
- **System monitoring and tuning**
  - spot storage bottlenecks and evaluate design changes
- **System validation (together with Pylon)**
  - compare effects of synthetic (replayed) workload vs. original measurements



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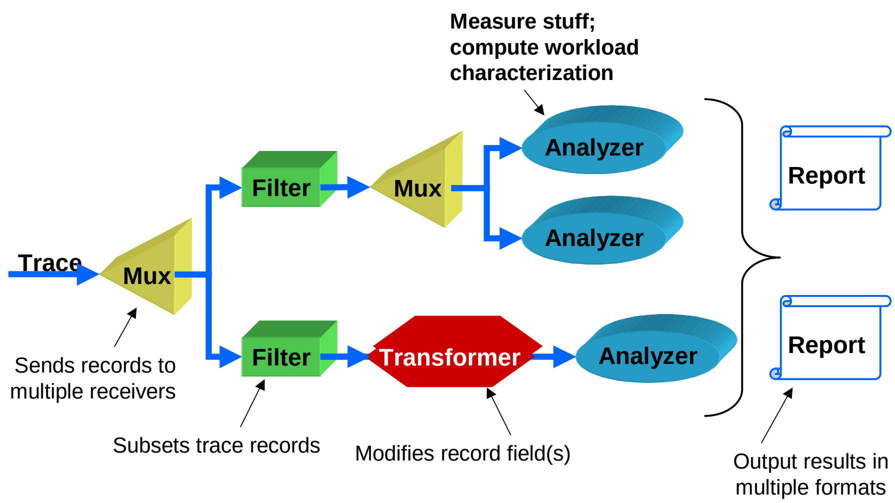
Rubicon – sample component tree



Workload modeling – case study

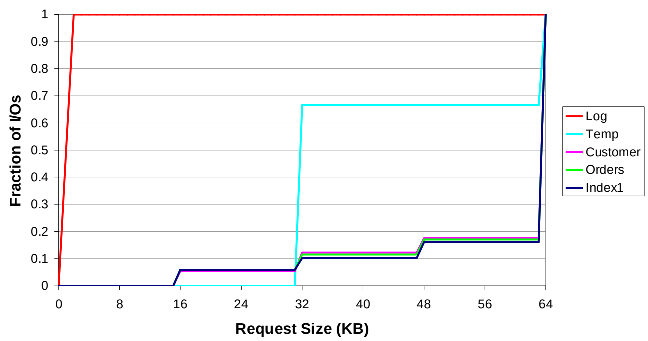
- **Decision support (DSS) database**
  - **Oracle**
  - **300 GB TPC-D database**
  - **Presentation focus: TPC-D Q5**

Also examining:

- **File system**
- **Email server**
- **Online transaction processing (OLTP) database**
- **Enterprise resource planning (ERP) database**
- **Scientific applications**
- **Web server**

Workload modeling – request size

- Dominated by larger (64KB) reads to tables
- Different behavior from different parts of the database:
  - table, indices, temp space, log



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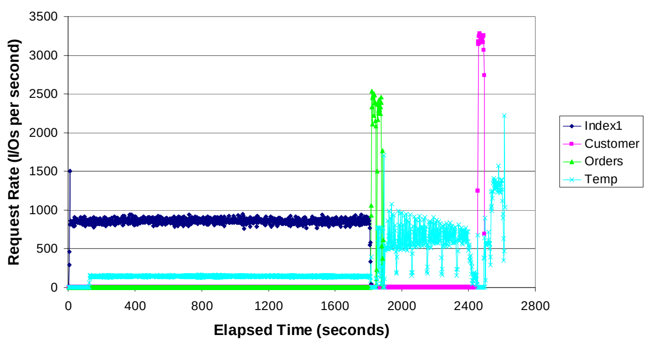
Workload modeling – I/O phasing

- Request rates vary widely
- Most multi-table queries have multiple phases
  - different tables active during different periods



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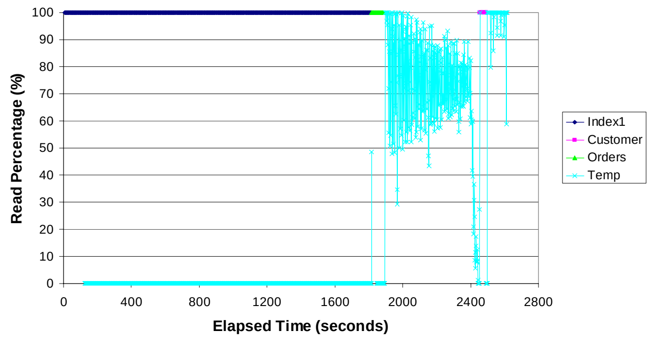
Workload modeling – read:write ratio

- “Read-only” workload exhibits writes!
  - read:write ratio varies over phases



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Workload modeling – lessons learned

- Lessons learned:
  - list of important characteristics is longer than you think
  - distributions, not averages, are important
- Some characteristics of interest:
  - request size distribution
  - request rate distribution
  - read:write ratio
  - spatial locality (e.g., sequentiality)
  - temporal locality (e.g., data re-references)
  - phased behavior
  - correlation between accesses to different parts of storage system
  - burstiness

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Workload modeling – related work

Workload characterization case studies

- File system tracing
  - [Ousterhout85, Miller91, Ramakrishnan92, Baker91, Gribble98]
- Network tracing
  - [Caceres91, Paxson94, Paxson97]
- I/O tracing
  - [Bates91, Ruemmler93, Gomez98, Hsu99]

Tools

- Offline trace gathering, analysis and visualization
  - [Grimsrud95, IBM99]
- Extensible trace analysis
  - Tramp [Touati91]
- Network packet filters
  - [Mogul87, McCanne93]
- Trace visualization
  - [Heath91, Malony91, Hibbard94, Eick96, Aiken96, Livny97]

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Issues in workload modeling

- What characteristics should we measure?
  - for workload regeneration
  - for QoS specification
  - for device performance prediction
- How to quantify these characteristics?
  - what metrics, and in how much detail?
  - ex: correlations, burstiness, spatial and temporal locality
- What's the relative importance of these properties?
- How to model the scaling behavior of applications?
  - ex: number of users, size of database
- How to provide semantic mapping between application operations and storage system requirements?

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Issues in workload modeling (cont.)

- How much does behavior vary between different apps running same workload?
  - ex: Oracle vs. Informix vs. DB2 vs. SQLServer
  - ex: NFS vs. CIFS
- How to model distributed applications and their interactions?
- How does NAS file workload characterization differ from block-oriented I/O characterization?

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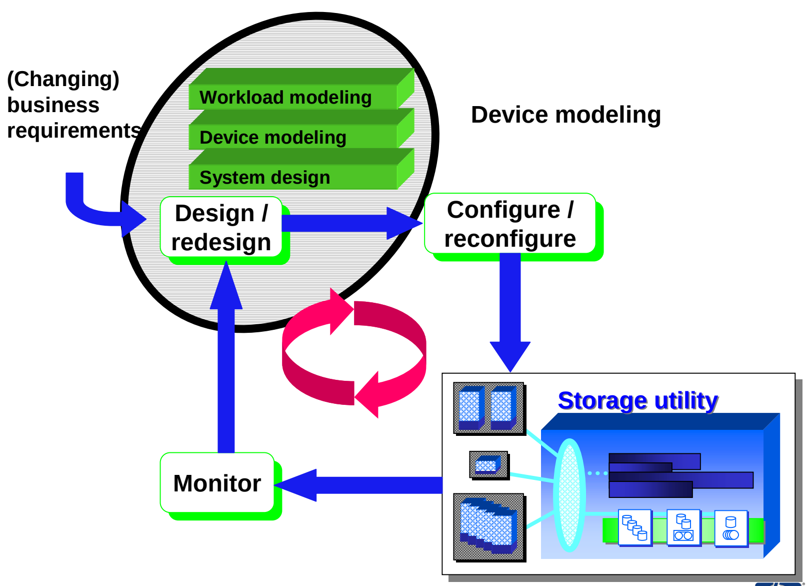
Customer lifecycle – the (re)design step



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Research challenge – device modeling

Goal: capture storage device characteristics in a predictive model:

- Capabilities
  - performance: transfer rate, positioning time, caching, ...
  - capacity
  - failure model
- Configuration options
- Costs

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Device modeling – SSP approach

- Fast, analytic models of device behavior
- Storage system = set of hosts + devices + fabric(s)
  - Hosts: where work is generated
    - (probably) support logical volume manager
  - Storage devices
    - provide LUNs (onto which workload stores/shards get mapped)
    - have capabilities (performance, capacity, availability) + cost
  - Storage fabric: connects hosts to storage devices
- (Simplified) device model example:
  - available device capacity > Σ capacity_store$_i$
  - available bandwidth > Σ requestRate_stream$_i$ * requestSize_stream$_i$
    - for streams that are “on” together

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Device modeling – building the model

- How to deal with:
  - non-deterministic experiments
    - e.g. measuring cache IO/s bandwidth -> known error bars
  - desired results that aren't the outcome of any single experiment
    - solve the system of equations to get results
  - reconfiguring a device between different experiments can be time-consuming
  - very long process -> failures must be tolerated (restart)
  - next point to consider may depend on outcomes of previous experiments
  - how good are a model's predictions?
- SSP approach: Pacioli
  - measurement of device-specific performance characteristics
  - validating complete models against the real system

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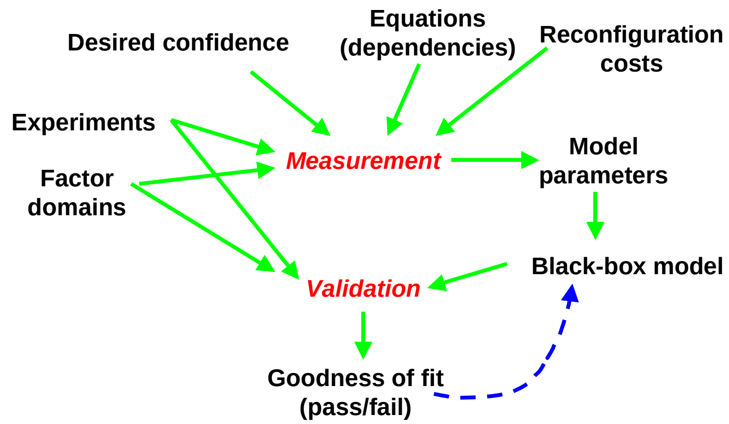
Pacioli structure



Future work: automatic calibration

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Device modeling – related work

- Ruemmler and Wilkes, 1993
  - accurate disk drive simulation model – prioritized components
  - detailed characteristics for two disk drives
- Worthington, et al., 1995
  - Black-box techniques for empirically extracting SCSI disk parameters
- Shriver, et al., 1997
  - disk drive model creatable by composing models of individual components
  - performance prediction dependent on input workload and predictions of lower-level models
- Pythia [Pentakalos, et al., 1997]
  - automatically builds and solves analytic model of storage system
  - inputs: graphical representation of system and workload
  - Pythia/WK: uses clustering algorithms to characterize workloads
- Disk arrays
  - [Thomasian94 , Merchant96, Menon97]

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Issues in device modeling

- What properties does the model need to capture?
  - to utilize workload characteristics
  - for accurate vs. fast predictions
- What's the relative importance of these properties?
- What's the right tradeoff between model accuracy and performance?
  - for simulations
  - for input to optimization
  - set of increasing fidelity device models
- Do we need to model hosts/servers to model storage system behavior adequately?
- (How) can we automatically extract model parameters?
- How to create device models that can use very complex workload characteristics?
  - ex: fractal characteristics
- How to incorporate availability/performability into models?
- How to model NAS devices?

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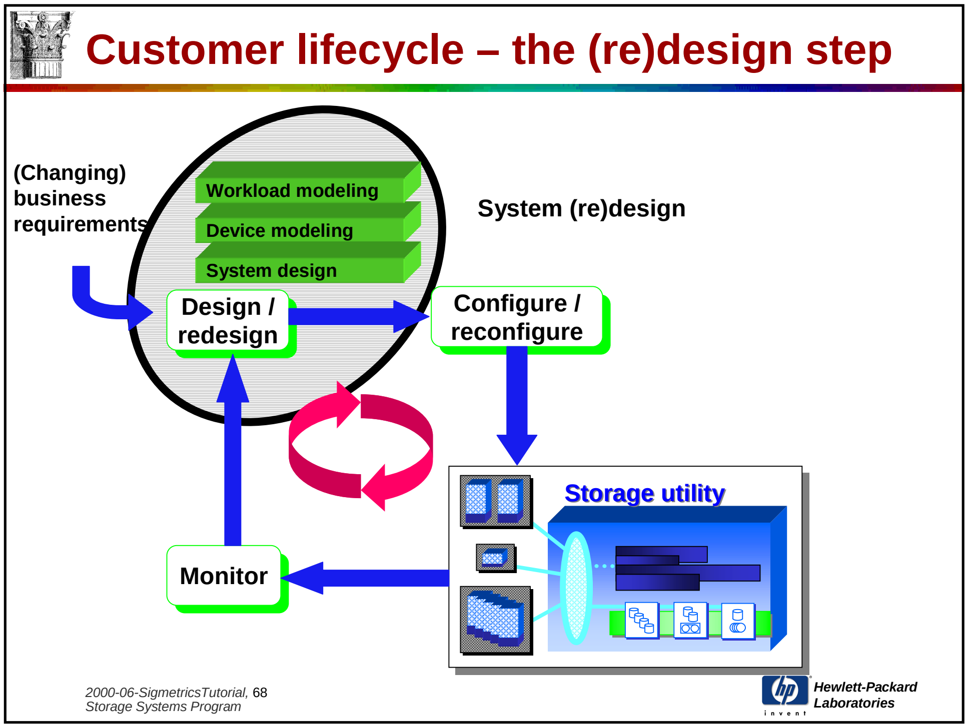
Customer lifecycle – the (re)design step
(Changing) business requirements
Workload modeling
Device modeling
System design
System (re)design
Design / redesign
Configure / reconfigure
Storage utility
Monitor
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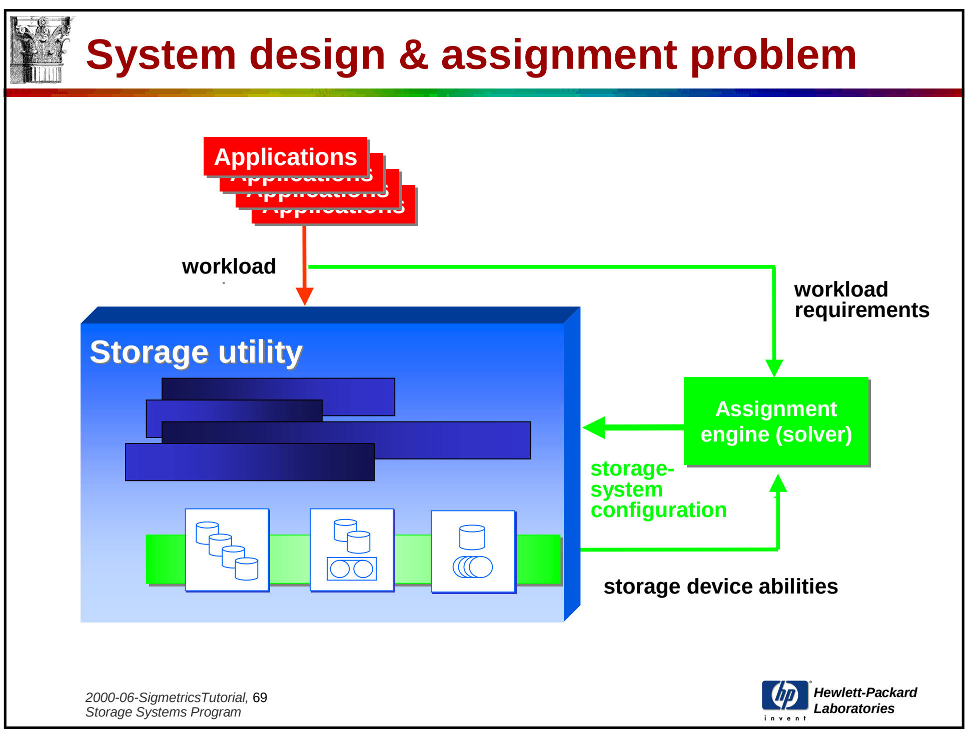
System design & assignment problem
Applications
workload
workload requirements
Storage utility
Assignment engine (solver)
storage-system configuration
storage device abilities
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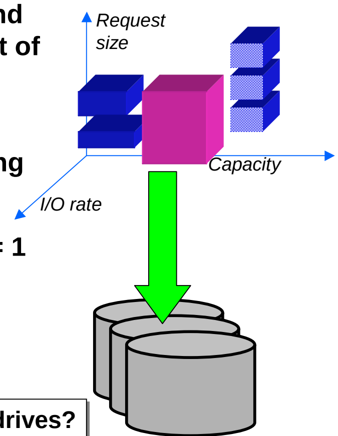
Research challenge – init. system design

- **Problem:**
  - convert workloads, business needs and device characteristics into assignment of stores and streams to devices
- **SSP approach: Forum**
  - constraint-based multi-dim. bin-packing
- **Sample constraints:**
  - number of devices store assigned to = 1
  - sum of store sizes <= capacity
  - sum of stream utilizations <= 1.0
- **Sample objective functions:**
  - minimize cost
  - balance load



**How many drives?
Holding which data?**

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Forum basics

- **Concise workload models**
  - sources:
    - library of models for common workload types
    - automatically characterized from running workload (Rubicon)
- **Fast, acceptable-fidelity device models**
  - executed in inner loop of optimizer
  - source: library of storage-device characterizations
- **Search-space exploration algorithms**
  - heuristics for trying “what ifs?”
    - good news: simple ones work well
  - utility-based objectives, modulated by business goals
    - minimum cost, maximum availability, balanced load, greater growth space, …

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Initial system design – disk arrays

- Problem:
  - extending the single disk solution (Forum) to disk arrays
  - the space of array designs is potentially huge:
    - LUN sizes and RAID levels, stripe unit sizes, disks in LUNs, prefetch multiplier and water marks, cache page size, read/write cache, …
      → more work needed before the Forum solver can run

SSP approach: Minerva

- Basic Minerva modules:
  - *Tagger:* tag stores with their type (RAID1, RAID5)
  - *Allocator:* estimate how many arrays needed to support this
  - *Design procedure:* configure each of the allocated arrays
  - *Forum solver:* map stores to LUNs
    [repeat until complete]
  - *Cleaner:* prune any unnecessary resources
  - *Optimizer* (Forum solver): can rearrangements decrease the cost or better balance the load?

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Minerva – how the modules work

- Tagger: rules tag each store according to how it's accessed
  - if capacity-bound, RAID5
  - if read-mostly, RAID1/0
  - …
- Allocator and designer: based on aggregate workload, buy and configure arrays that can do the job
  - find cheapest set that a priori may work
- Forum solver: assign stores to LUNs
- Cleaner: discard disks, cabinets, busses, … that service only empty LUNs
- Optimizer: use Forum solver with different objective functions to generate alternative solutions; then pick best
  - mincost on final set: can cost be reduced further?
  - optimize load balancing (utilization)

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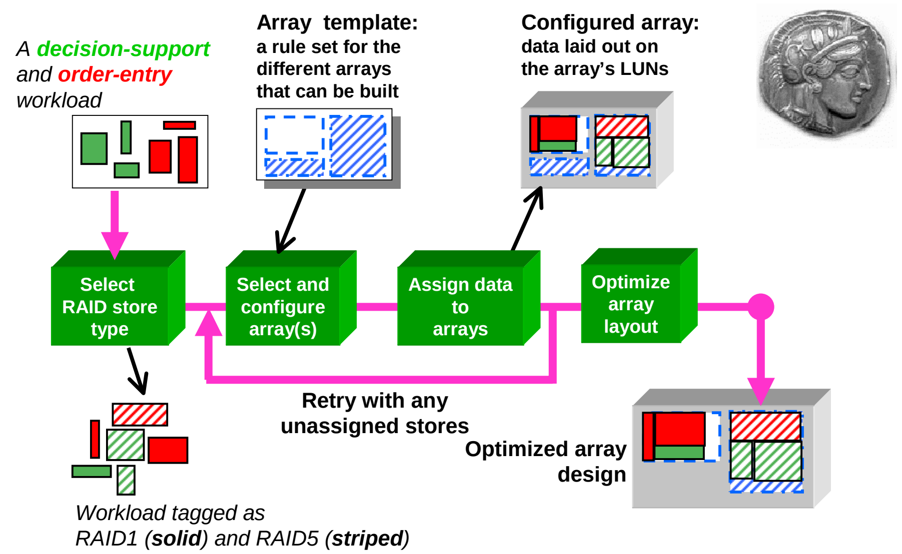
Minerva – disk array system design



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Initial system design - related work

- **Storage management [Gelb89]**
  - Logical view of data separate from physical device characteristics – simplifies management
- **File assignment**
  - Files placed on storage devices with aim of optimizing objective(s)
  - [Dowdy82, Wolf89, Pattipati90, Awerbuch93]
- **Optimization algorithms**
  - Bin-packing heuristics [Coffman84]
  - Toyoda gradient [Toyoda75]
  - Simulated annealing [Drexl88]
  - Relaxation approaches [Pattipati90, Trick92]
  - Genetic algorithms [Chu97]

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Issues in system design and allocation

- What optimization algorithms are most effective?
- What optimization objectives and constraints produce reasonable designs?
  - ex: cost of reconfiguring system
- What's the right part of the storage design space to explore?
  - ex: RAID level vs. stripe unit size vs. cache mgmt parameters
- What are reasonable general guidelines for tagging a store's RAID level?
- What (other) decompositions of the design and allocation problem are reasonable?
- How to generalize system design?
  - for SAN environment
  - for host and applications

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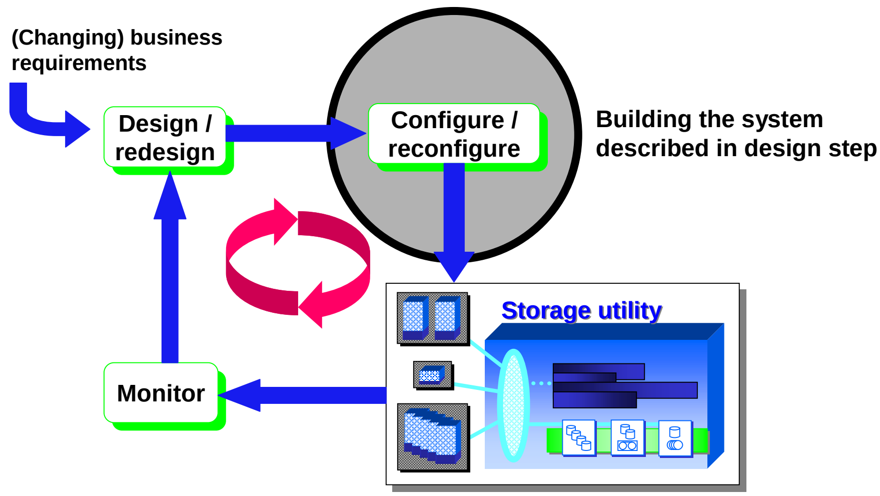
Customer lifecycle – build/configure step



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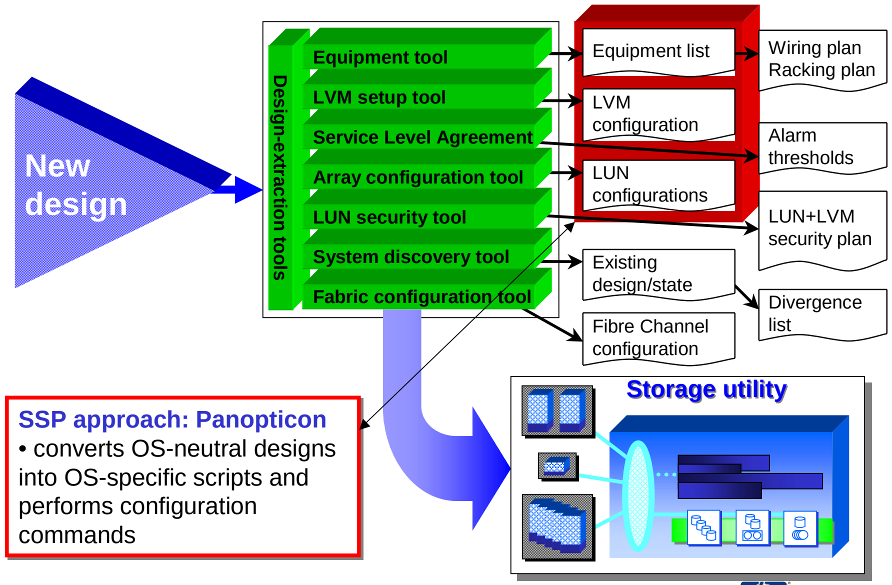
Research challenge – configuration



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Issues in configuration

- **How to do system discovery?**
  - **ex: existing state, presence of new devices**
  - **dealing with inconsistent information**
  - **in a scalable fashion**
- **How to abstractly describe storage devices?**
  - **for system discovery output**
  - **for input to tools that perform changes**
- **How to automate the physical design process?**
  - **ex: physical space allocation, wiring, power, cooling**

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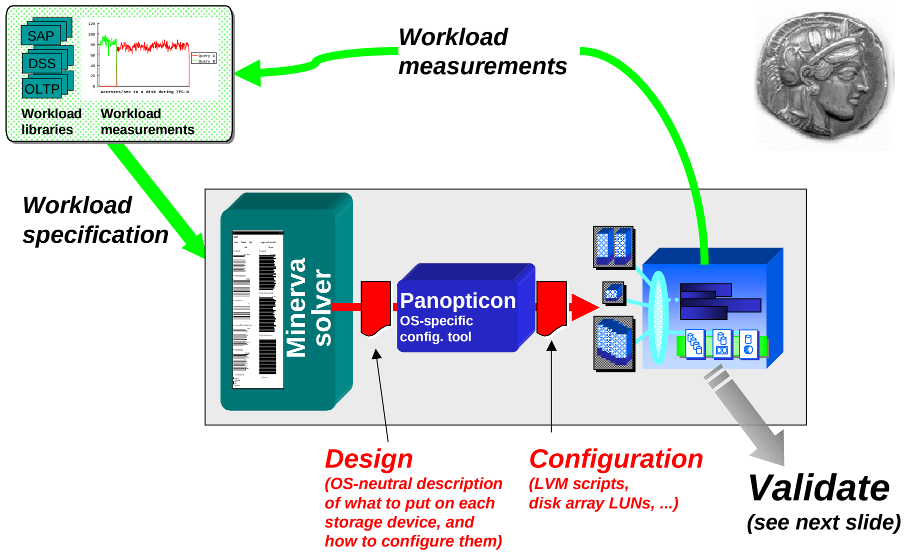
Putting it all together – TPC-D case study



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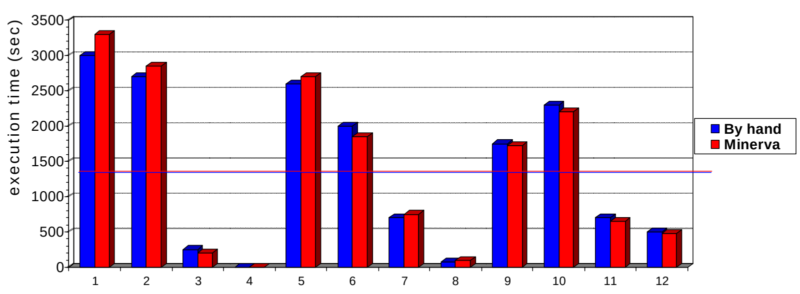
Putting it all together – TPC-D case study

- **Initial design: human expert**
  - 30 disks
  - measured workload used as Minerva input
- **Minerva design: automatic!**
  - 16 disks
  - same performance (within 3%)



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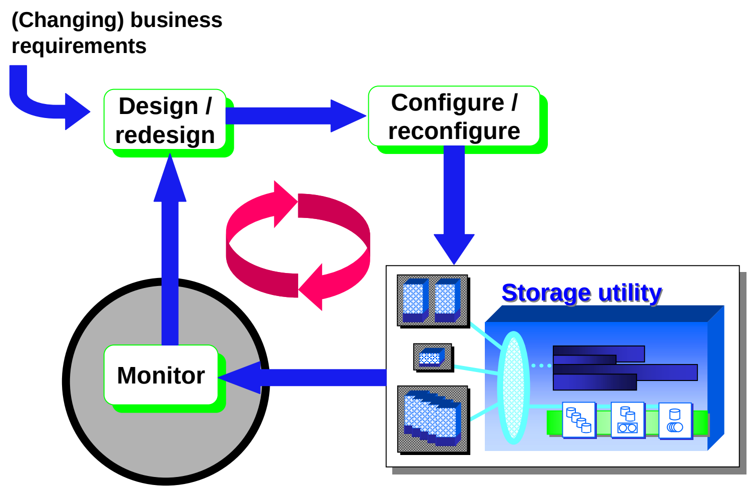
Customer lifecycle: system monitoring



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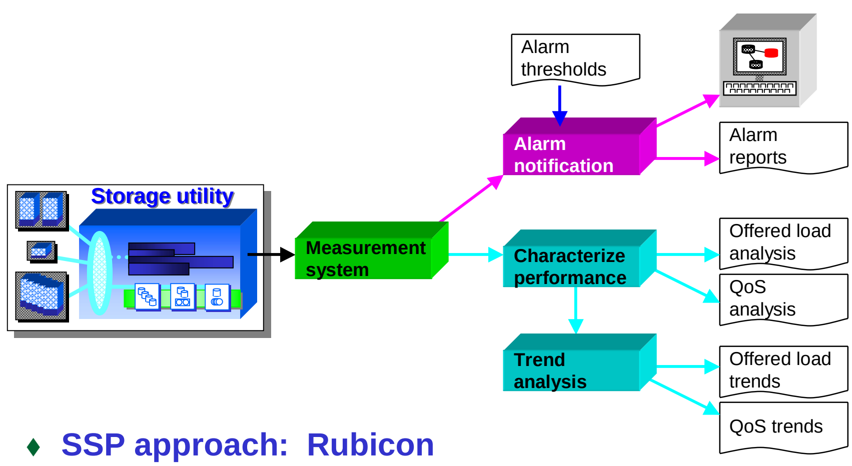
Research challenge – online monitoring



- SSP approach: Rubicon
- Related work: online performance monitoring
  - Paradyn [Miller95] and Pablo [Reed93]

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Issues in online monitoring

- What quantities must be monitored?
  - to detect component failures
  - to detect performance bottlenecks
  - to enforce QoS requirements/detect QoS violations
  - to detect performance trends
- How to monitor in a scalable fashion?
- How to monitor in a flexible fashion?
  - ex: attributes that are specific to one type of device
- How to translate between different levels of abstraction?
  - ex: LUNs vs. logical volumes vs. database tables
- What policies and thresholds should be used for generating alarms?

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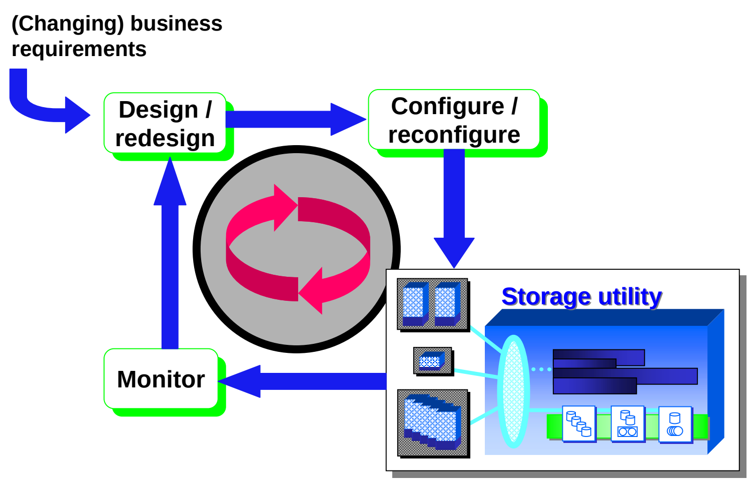
Customer lifecycle – cont. improvement



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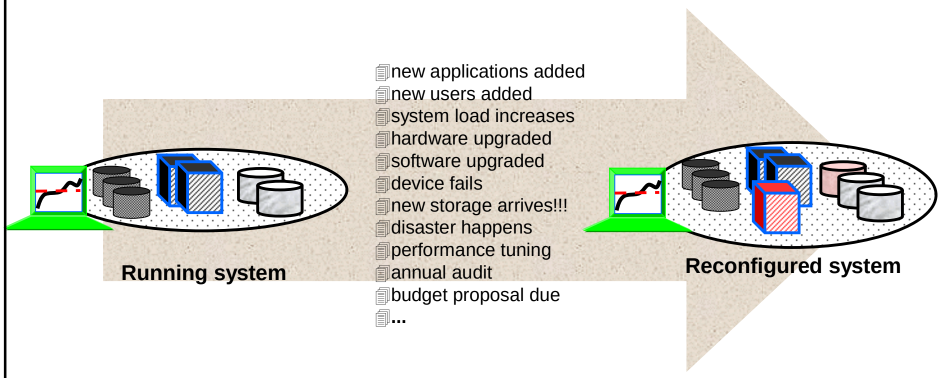
Research challenge – reconfiguration



- **System should automatically respond to workload and device needs to meet user performance and availability goals**

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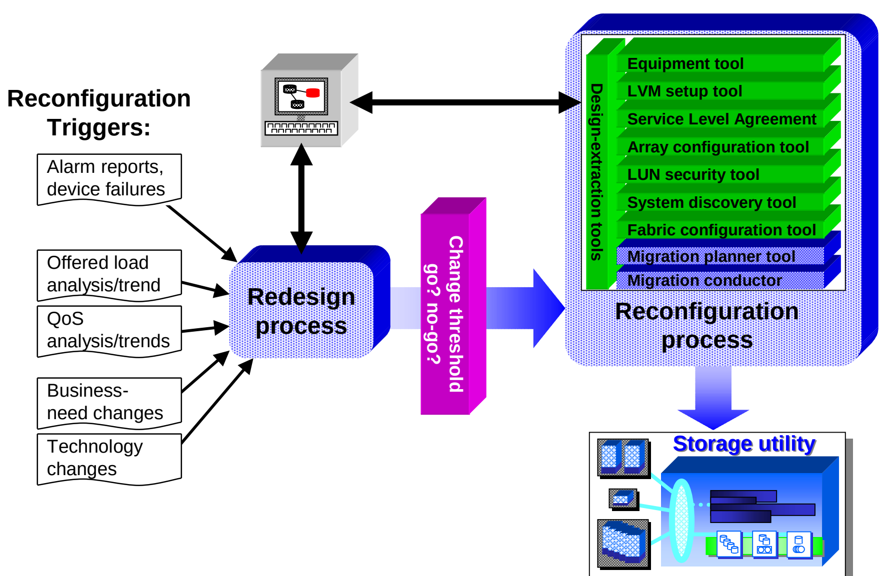
Research challenge – reconfiguration



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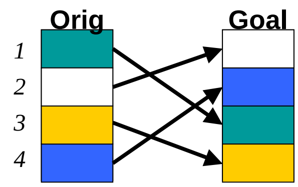
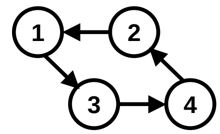
Research challenge – reconfiguration



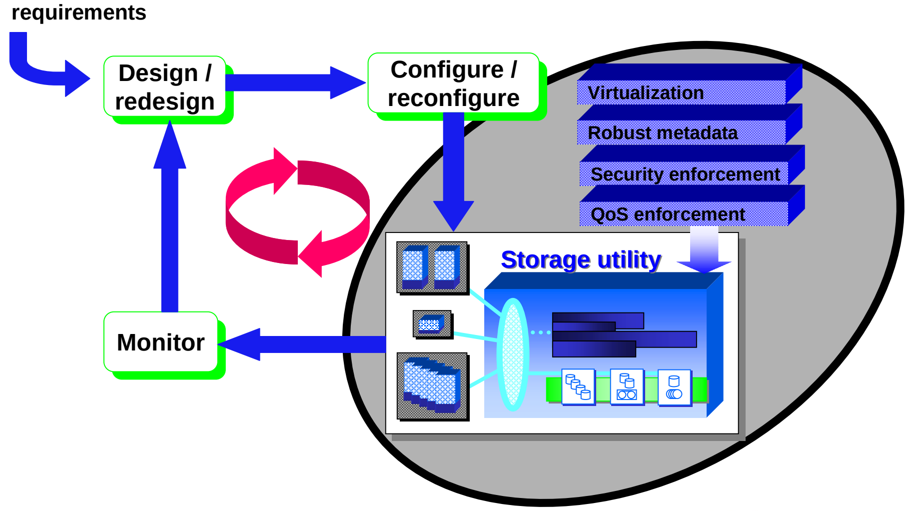
- Events trigger redesign decision
  - How do we decide when to reconfigure?
- Solver creates new system assignment
- Reconfiguration inputs:
  - current system configuration/assignment
  - desired system configuration/assignment
- 1. Build a migration plan
  - How to devise a plan for data movement with general constraints?
    - ex: capacity, performance, availability
  - How to generalize for variable-sized data?
  - How to allow parallel execution?
  - How much free space is needed?



- 2. Make it happen – *online*
  - Runtime system: combination of host-side virtualization, metadata management, and storage device hooks

Customer lifecycle – the running system

(Changing) business requirements



Palladio – SSP’s runtime system approach

- **Automatic responses to system load changes**
  - goal-directed, not policy-based
  - mechanisms for attribute management
- **Key issues**
  - How to provide online data migration?
    - “virtualization” of metadata
    - mechanisms for online data migration, replication
  - How to provide self-management?
    - automatic inclusion of new resources
    - automatic failure handling
  - How to recover from disasters?
    - robust metadata management
    - multiple site support
  - How to enforce security and QoS in shared environment?

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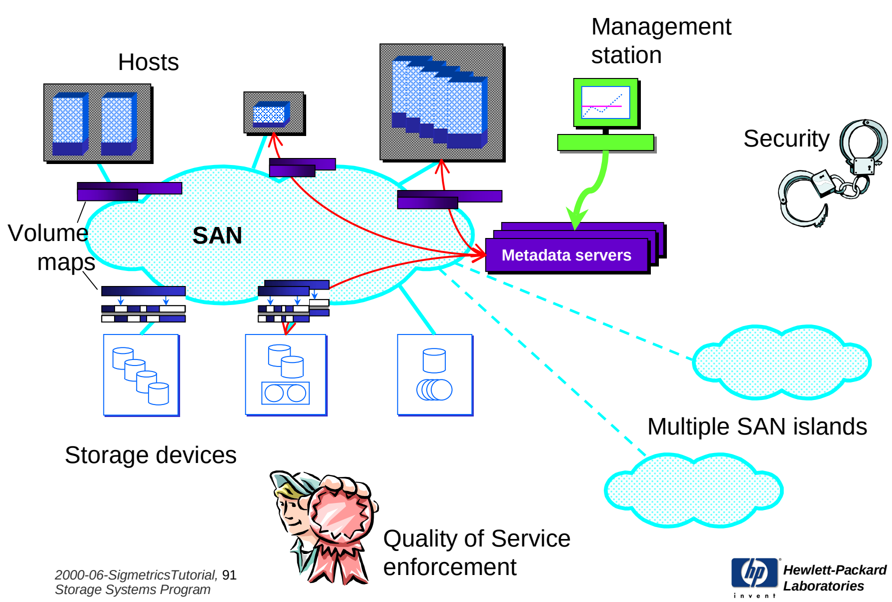
Palladio system architecture



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Research challenge – runtime system

- Ensuring metadata is always available
  - Even in the face of network partitioning [Golding99]
- Managing concurrency at the large scale
  - Optimistic concurrency control protocols [Amiri00]
- Enforcing security in a multi-host environment
  - Has to be done directly at storage device in a shared-resource environment
  - Carnegie Mellon NASD [Gobioff99, Gibson98]
- QoS enforcement (e.g. Service Level Agreements)
  - How should these be specified?
  - What portions should be enforced by which component?
  - How can violations be detected? Handled? At what cost?
  - [Golubchik99, Bruno99, Wijayaratne00]

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Runtime system related work

- CMU network-attached disks
  - disks present file-like objects
  - many disks aggregated to make system
  - [Gibson97, Gibson98]
- Distributed storage service
  - MIT Logical disks [deJonge93]
  - Compaq/DEC SRC Petal [Lee96]
  - U of Arizona Swarm [Hartman99]
- Distributed file systems
  - CMU Andrew FS [Howard88]
  - Berkeley Zebra [Hartman93]
  - Berkeley xFS [Anderson95]
  - Compaq SRC Frangipani (FS for Petal) [Thekkath97]

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Additional research challenges

- How do we design SAN fabrics automatically?
- What's the right interface for storage?
  - files vs. blocks
  - NAS vs. SAN
  - how do we ensure secure storage?
  - how much does this matter for storage management?
- How can we exploit device intelligence to make storage management easier?
- How do we describe maintainability and availability?

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SAN fabric design

- Problem description
  - given: flows betw. endpoints and SAN characteristics
  - return: set of internal nodes and node-node links (incl. flows)
  - must satisfy:
    - flow requirements, link and node constraints, connectivity constraints
- Current state of the art
  - designs are done by hand, using a few simple topologies
- Automation hasn't proven straightforward
  - degree-constraints seems unusual
  - divide-and-conquer seems unhelpful
- "Extra credit" items are very important
  - fault tolerance: designing for all possible failure cases
  - multiple layers of switches/hubs possible

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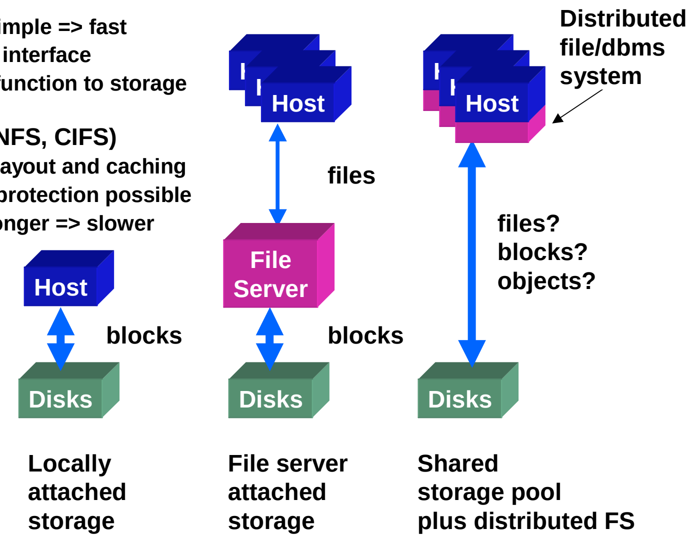
Storage interface – blocks vs. files?

- Blocks (SCSI)
  - \+ critical path simple => fast
  - – very "simple" interface
  - – hard to push function to storage device
- Files (Netware, NFS, CIFS)
  - \+ can optimize layout and caching
  - \+ finer-grained protection possible
  - – critical path longer => slower



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Exploiting device intelligence

- Observations
  - – processing capabilities, memory capacity, and networking ability of storage devices increasing
  - – aggregate computational ability and aggregate bandwidth at devices are greater than at central processors
- Goal
  - – use storage devices to run application code and improve performance of data-intensive applications
- Focus to date
  - – file system functionality in devices
    - [Wilkes92, Cao93, Wang99]
  - – database and data processing functionality in devices
    - [Keeton98, Riedel98, Acharya98, Uysal00, Riedel00]
    - revisits database machine work from late 1970s – early 1980s
- Potential future work
  - – storage management functionality in devices
    - ex: data migration, resource discovery and mgmt, monitoring

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Describing manageability & availability

- Observations
  - computer architecture and operating systems community shift in research interest: non-performance topics
  - difficulty of maintaining large systems
- Goals
  - enumerate important factors in managing large systems
  - describe (quantitative) metrics for evaluating system manageability/maintainability
- Initial efforts
  - availability metrics [Brown00]

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Summary – storage mgmt challenges

- Workload characterization/modeling
- Storage device modeling
- Initial system design
- System configuration
- Online system monitoring
- System reconfiguration
- Runtime system
- SAN fabric design
- Storage system interfaces
- Exploiting smart devices
- Describing/Quantifying manageability

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Summary – underlying trends

- Commoditization of hardware
  - software+services are the real differentiators, not hardware
- Network upheavals (FC, Infiniband, 1-10Gb's Ethernet, IP)
  - Internet protocols becoming dominant ("when, not if")
  - block servers -> file abstractions (whether/when?)
- Cheap distributed CPU cycles
  - storage appliances, smart storage devices, function shipping
- Demands for predictability (aka QoS)
  - guarantees for availability, performance, security
- The services revolution
  - rent-a-Terabyte?

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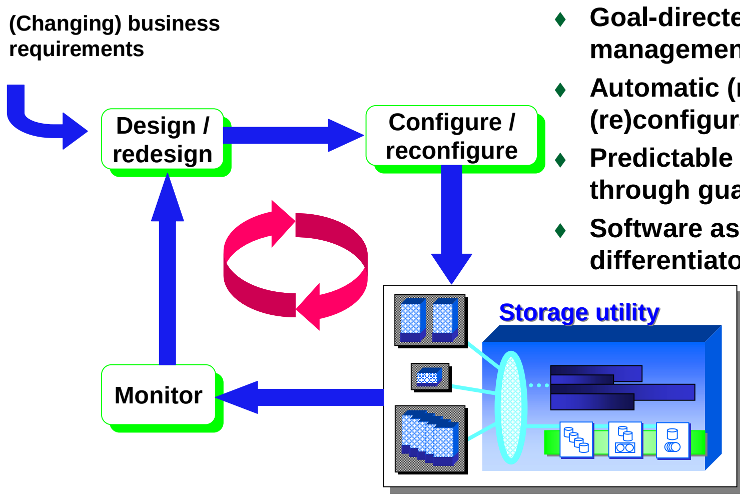
Conclusions – key ideas



Just a few Big Ideas:

- Goal-directed self-management
- Automatic (re)design and (re)configuration
- Predictable behavior through guarantees
- Software as the key differentiator

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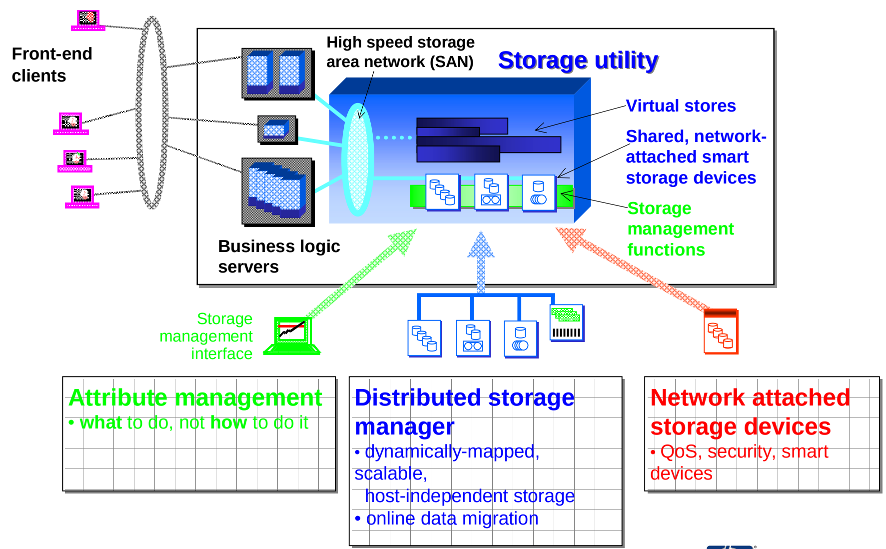
Conclusions - the storage utility



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Conclusions

- Storage systems represent an interesting technical (and commercial) opportunity
  - data is important to people
  - large scale
  - very high performance
  - extreme availability/fault-tolerance needs
- Rich storage-related research topics
  - optimization problems
  - measurement and modeling problems
  - distributed systems problems

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  - David Nagle & Garth Gibson (Carnegie Mellon)

- To learn more:
  - **www.hpl.hp.com/SSP**

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Sources for additional information

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