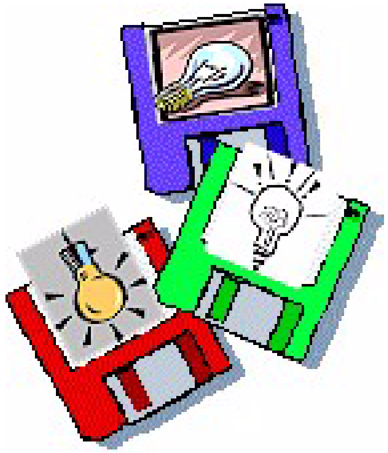


# Active Disks - Remote Execution for Network-Attached Storage

**Erik Riedel**

Parallel Data Laboratory,
Center for Automated Learning and Discovery
Carnegie Mellon University
*www.pdl.cs.cmu.edu/Active*

# Outline

**Motivation**

**Computation in Storage**

**Performance Model**

**Applications & Prototype**

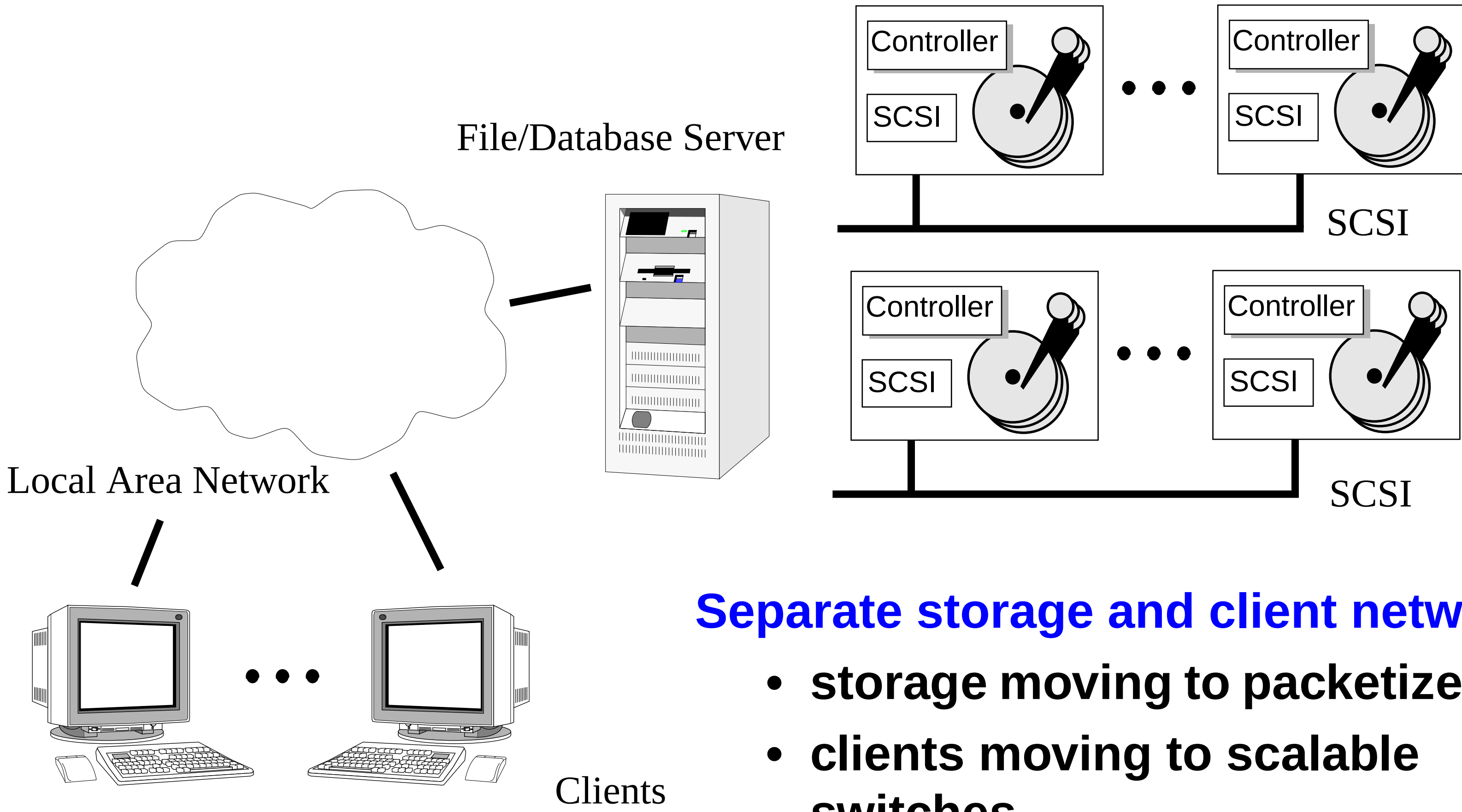
**Drive-Specific Functionality**

**Related Work**

**Contributions & Future Work**

# Yesterday's Server-Attached Disks

## Store-and-forward data copy through server machine



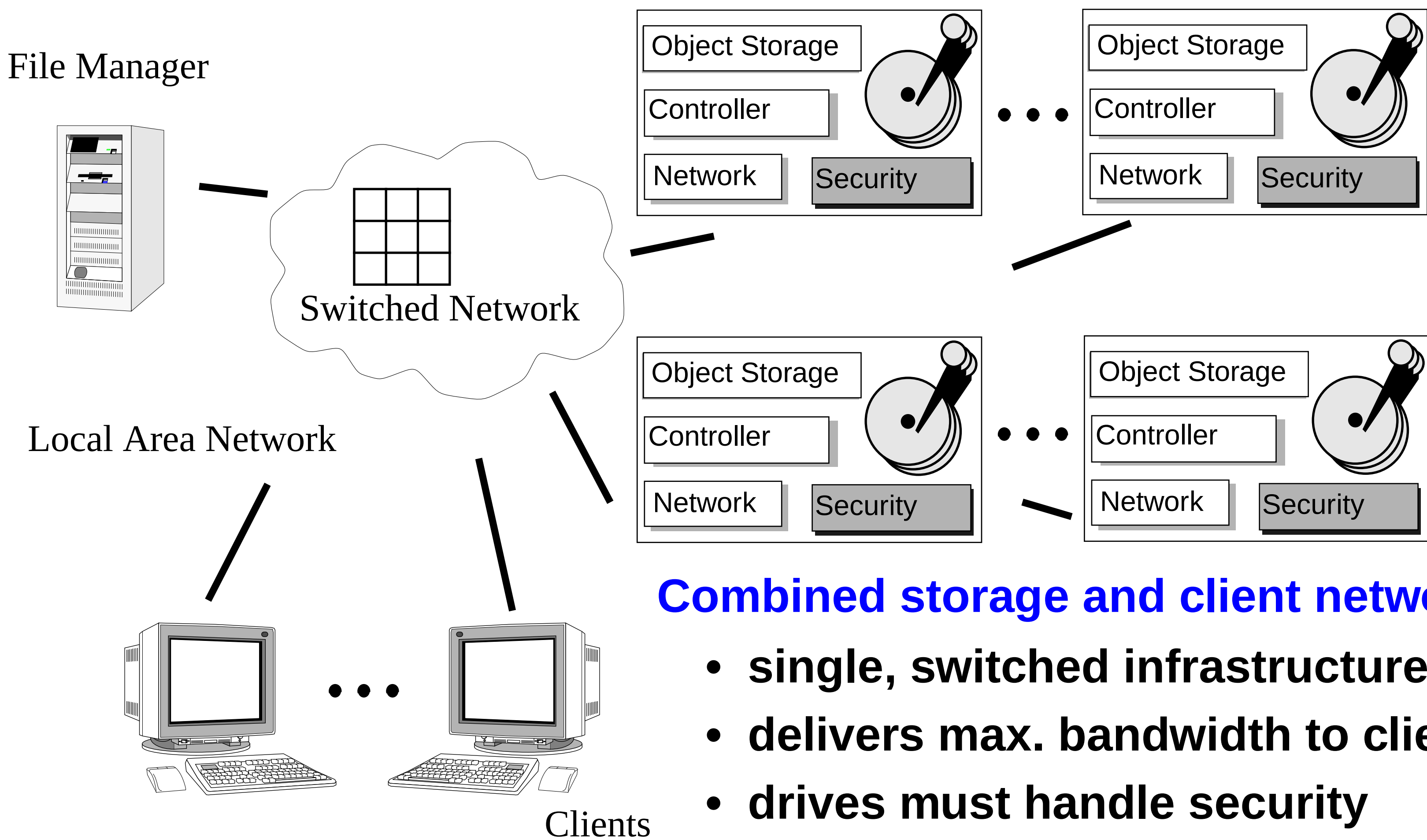

**Separate storage and client networks**

- **storage moving to packetized FC**
- **clients moving to scalable switches**

# Network-Attached Secure Disks

## Eliminate server bottleneck w/ network-attached

- server scaling [SIGMETRICS ‘97]
- object interface, filesystems [CMU-CS ‘98]
- cost-effective, high bandwidth [ASPLOS ‘98]




## Combined storage and client networks

- single, switched infrastructure
- delivers max. bandwidth to clients
- drives must handle security

# Outline

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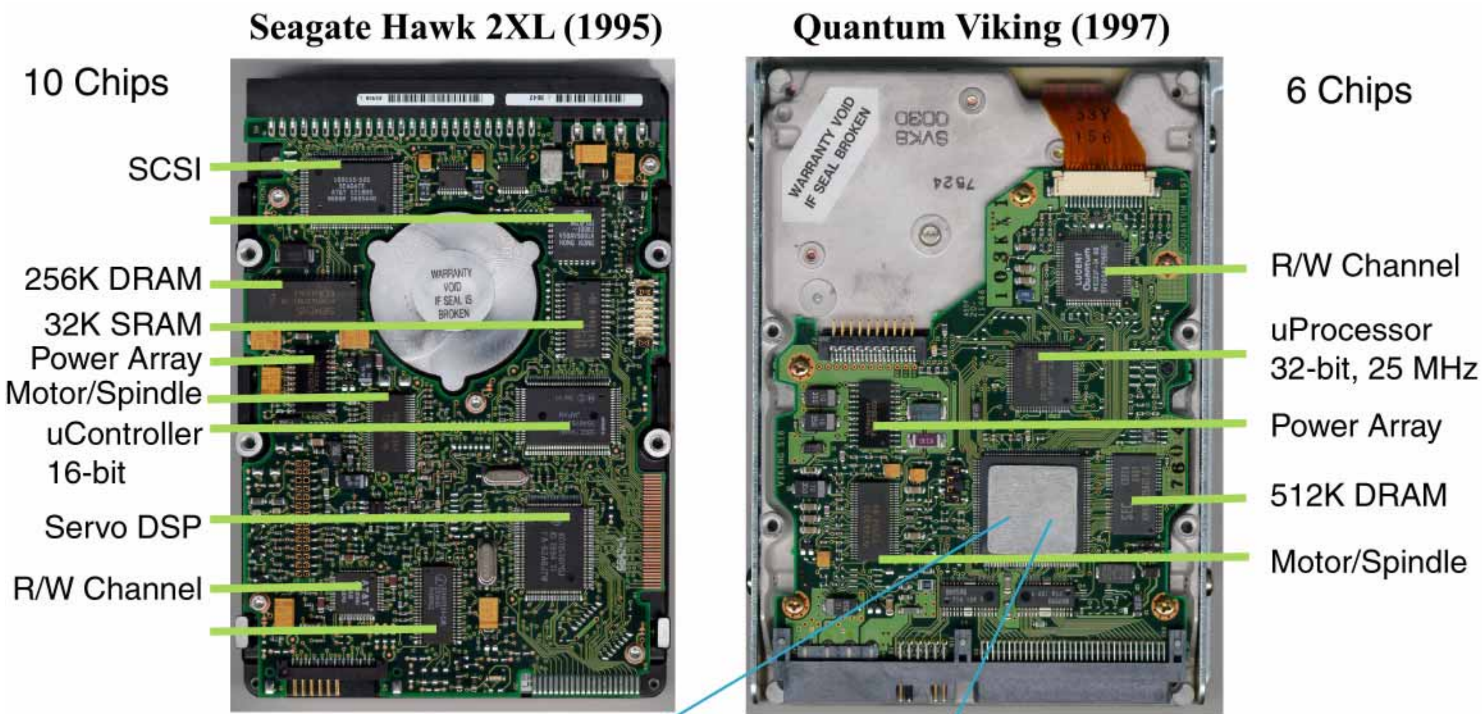
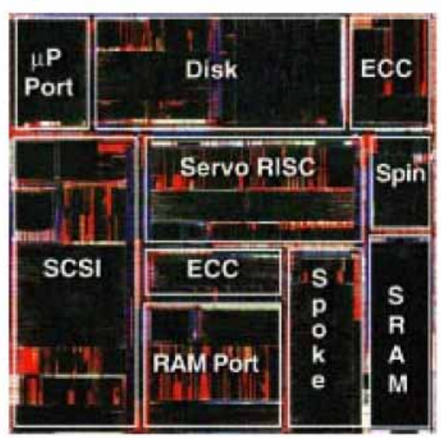
# Evolution of Disk Drive Electronics

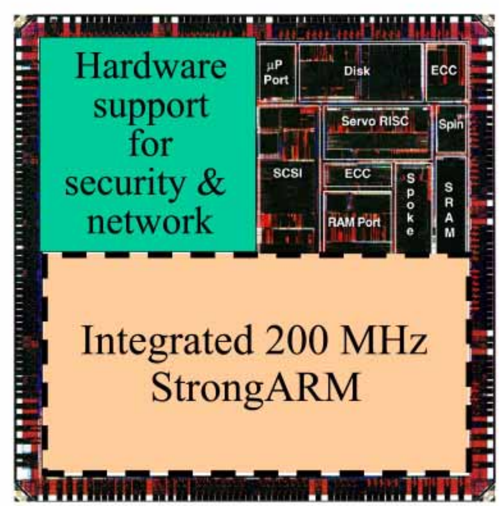



## Integration

- reduces chip count
- improves reliability
- reduces cost
- future integration to processor on-chip
- but there must be at least *one* chip




Trident ASIC




Future Generation ASIC

# Excess Device Cycles Are ~~Coming~~ Here

## Higher and higher levels of integration in electronics

- **specialized drive chips combined into single ASIC**
- **technology trends push toward integrated control processor**
- **Siemens TriCore - 100 MHz, 32-bit superscalar today**
  - **to 500 MIPS within 2 years, up to 2 MB on-chip memory**
- **Cirrus Logic 3CI - ARM7 core today**
  - **to ARM9 core at 200 MIPS in next generation**

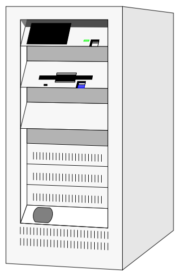
## High volume, commodity product

- **145 million disk drives sold in 1998**
  - **about 725 petabytes of total storage**
- **manufacturers looking for value-added functionality**

# Opportunity

## TPC-D 300 GB Benchmark, Decision Support System

Database Server



Digital AlphaServer 8400
- 12 x 612 MHz 21164
- 8 GB memory
- 3 64-bit PCI busses
- 29 FWD SCSI controllers

**= 7,344 total MHz**

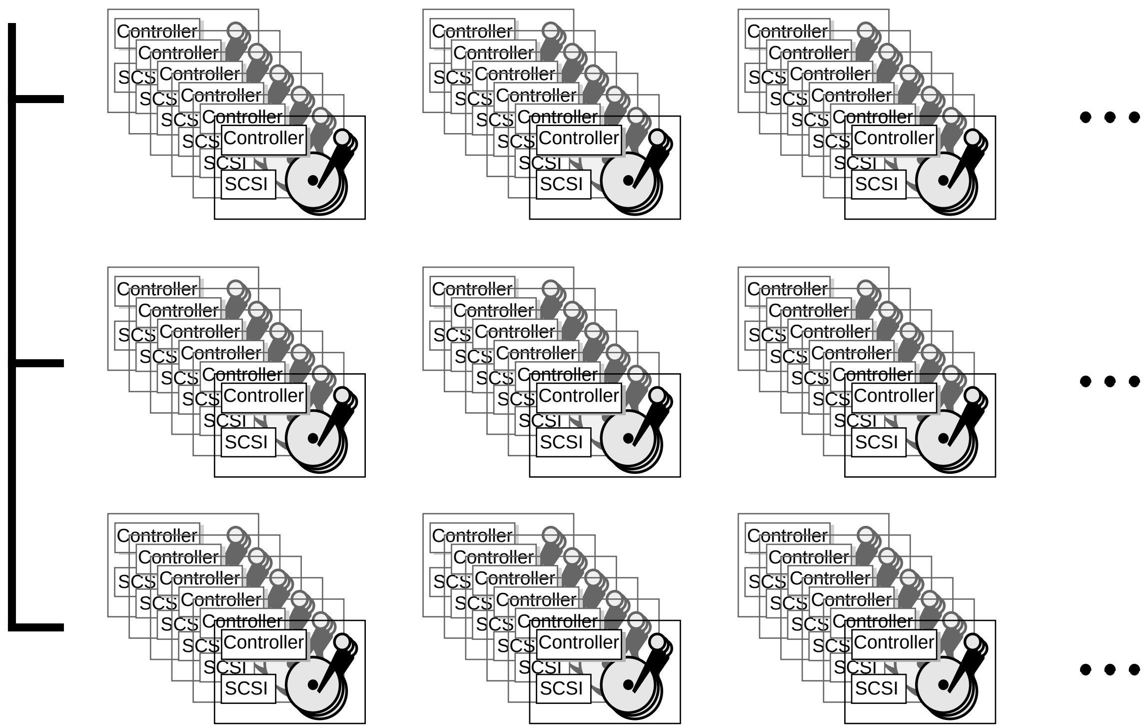
***3 x 266 = 798 MB/s***

***29 x 40 = 1,160 MB/s***

Storage
- 520 rz29 disks
- 4.3 GB each
- 2.2 TB total

**= 104,000 total MHz (with 200 MHz drive chips)**

***= 5,200 total MB/s (at 10 MB/s per disk)***



# Opportunity

## Large database systems - lots of disks, lots of power

| System | Processing (MHz) | | Data Rate (MB/s) | |
|---|---|---|---|---|
| | CPU | Disks | I/O Bus | Disks |
| Compaq Proliant TPC-C | 4 x 400=**1,600** | *141* x 25=**3,525** | **133** | **1,410** |
| Microsoft Terraserver | 8 x 440=**3,520** | *324* x 25=**8,100** | **532** | **3,240** |
| Compaq AlphaServer 500 TPC-C | 1 x 500=**500** | *61* x 25=**1,525** | **266** | **610** |
| Compaq AlphaServer 8400 TPC-D | 12x612=**7,344** | *521* x 25=**13,025** | **532** | **5,210** |

- **assume disk offers equivalent of 25 host MHz**
- **assume disk sustained data rate of 10 MB/s**

## Lots more cycles and MB/s in disks than in host

- **main bottleneck is backplane I/O bandwidth**

# Advantage - Active Disks

***Active Disks*** **execute application-level code on drives**

## Basic advantages of an Active Disk system

parallelism →
- **parallel processing** - lots of disks

compute at the edges →
- **bandwidth reduction** - filtering operations are common
- **scheduling** - little bit of "strategy" can go a long way

## Characteristics of appropriate applications

- **execution time dominated by data-intensive "core"**
- **allows parallel implementation of "core"**
- **cycles per byte of data processed -** ***computation***
- **data reduction of processing -** ***selectivity***

# Example Application

## Data mining - association rules [Agrawal95]

- retail data, analysis of "shopping baskets"
- frequent sets summary counts
- count of *1-itemsets* and *2-itemsets*
- milk & bread => cheese
- diapers & beer

## Partitioning with Active Disks

- each drive performs count of its portion of the data
- counts combined at host for final result

# Outline

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# Performance Model

## Application Parameters

$N_{in}$ = number of bytes processed

$N_{out}$ = number of bytes produced

$w$ = cycles per byte

$t$ = run time for traditional system

$t_{active}$ = run time for active disk system

$d$ = number of disks

## System Parameters

$s_{cpu}$ = CPU speed of the host

$r_d$ = disk raw read rate

$r_n$ = disk interconnect rate

## Active Disk Parameters

$s_{cpu}'$ = CPU speed of the disk

$r_d'$ = active disk raw read rate

$r_n'$ = active disk interconnect rate

## Traditional vs. Active Disk Ratios

$\alpha_N = N_{in} / N_{out}$ $\alpha_d = r_d' / r_d$ $\alpha_n = r_n' / r_n$ $\alpha_s = s_{cpu}' / s_{cpu}$

# Performance Model

Traditional server:

$$t = max\left(\frac{N_{in}}{d \cdot r_d}, \frac{N_{in}}{r_n}, \frac{N_{in} \cdot w}{s_{cpu}}\right) + (1 - p) \cdot t_{serial}$$

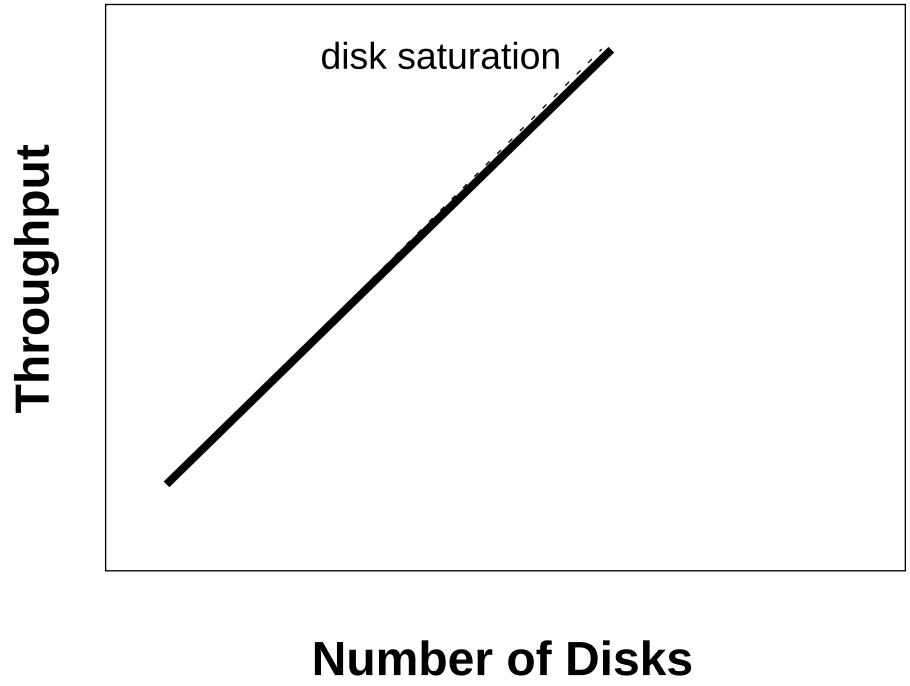
disk network cpu overhead

Active Disks:

$$t_{active} = max\left(\frac{N_{in}}{d \cdot r_d'}, \frac{N_{out}}{r_n'}, \frac{N_{in} \cdot w}{d \cdot s_{cpu}'}\right) + (1 - p) \cdot t_{serial}$$

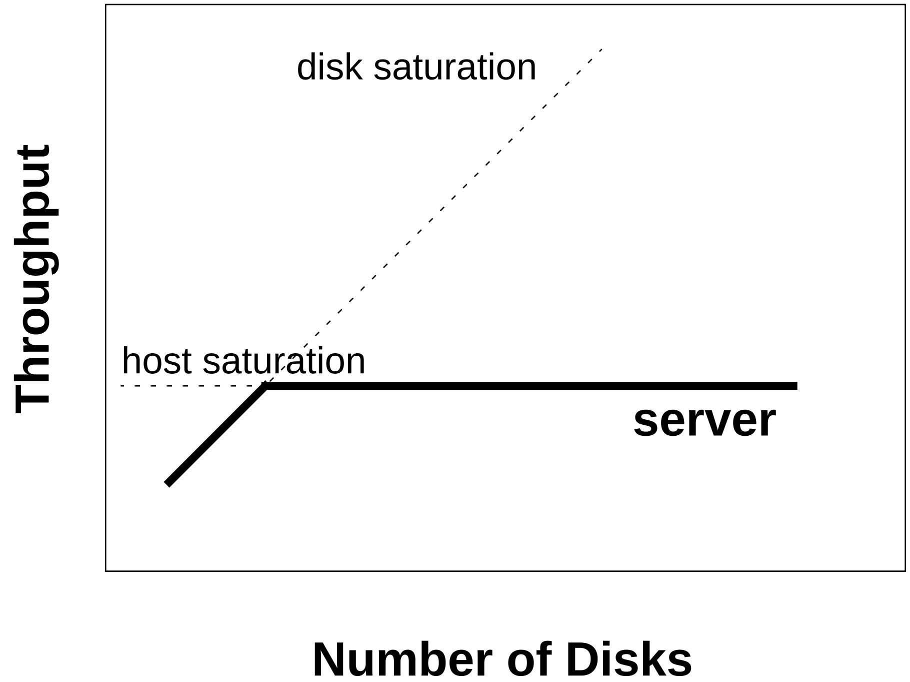
# Throughput Model

## Scalable throughput



# Throughput Model

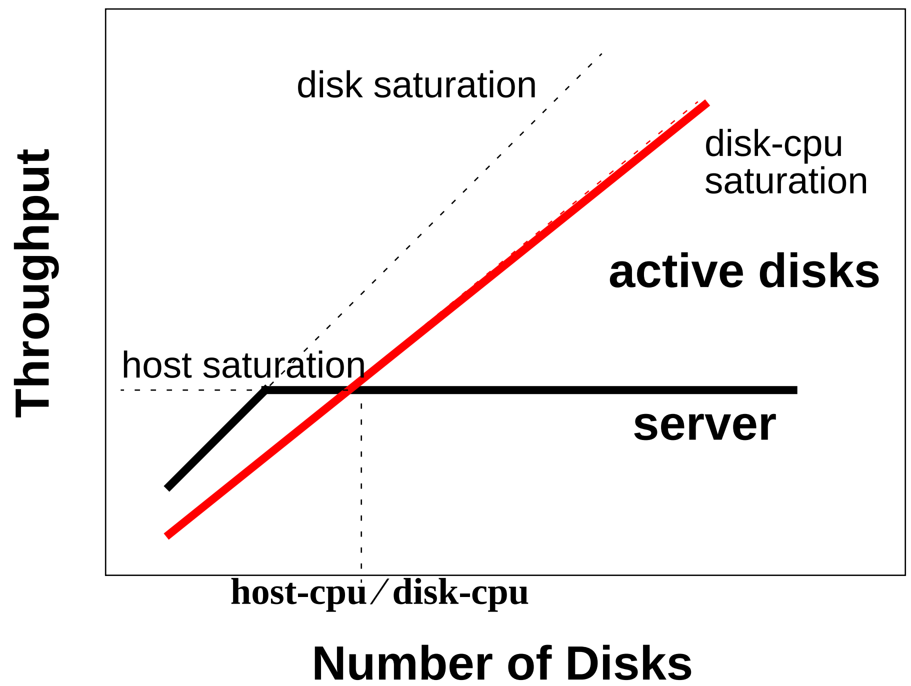
## Scalable throughput



# Throughput Model

## Scalable throughput

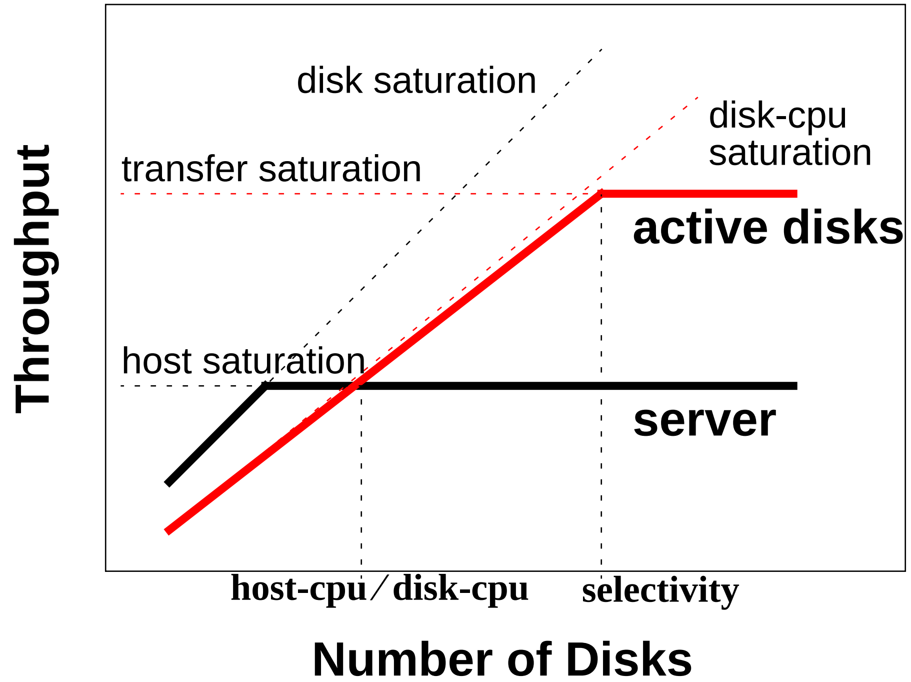
- **speedup = (#disks)/(host-cpu-speed/disk-cpu-speed)**
- **(host-cpu/disk-cpu-speed) ~ 5  (two processor generations)**



# Throughput Model

## Scalable throughput

- **speedup** = (#disks)/(host-cpu-speed/disk-cpu-speed)
- (host-cpu/disk-cpu-speed) ~ 5 (two processor generations)
- **selectivity** = #bytes-input / #bytes-output



# Outline

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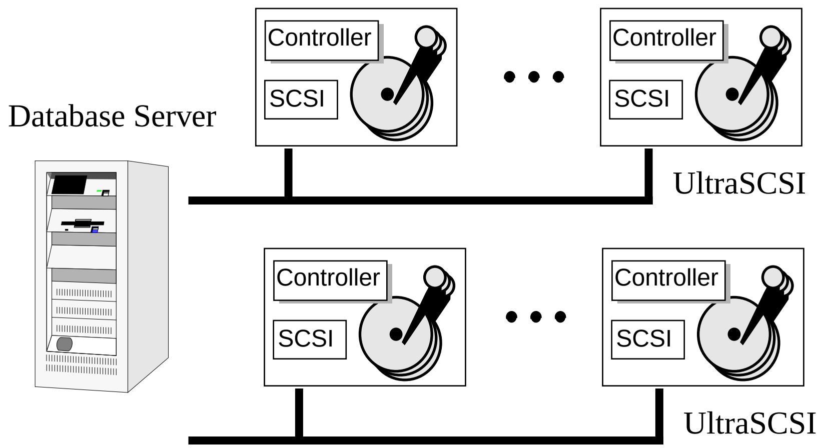
# Prototype Comparison

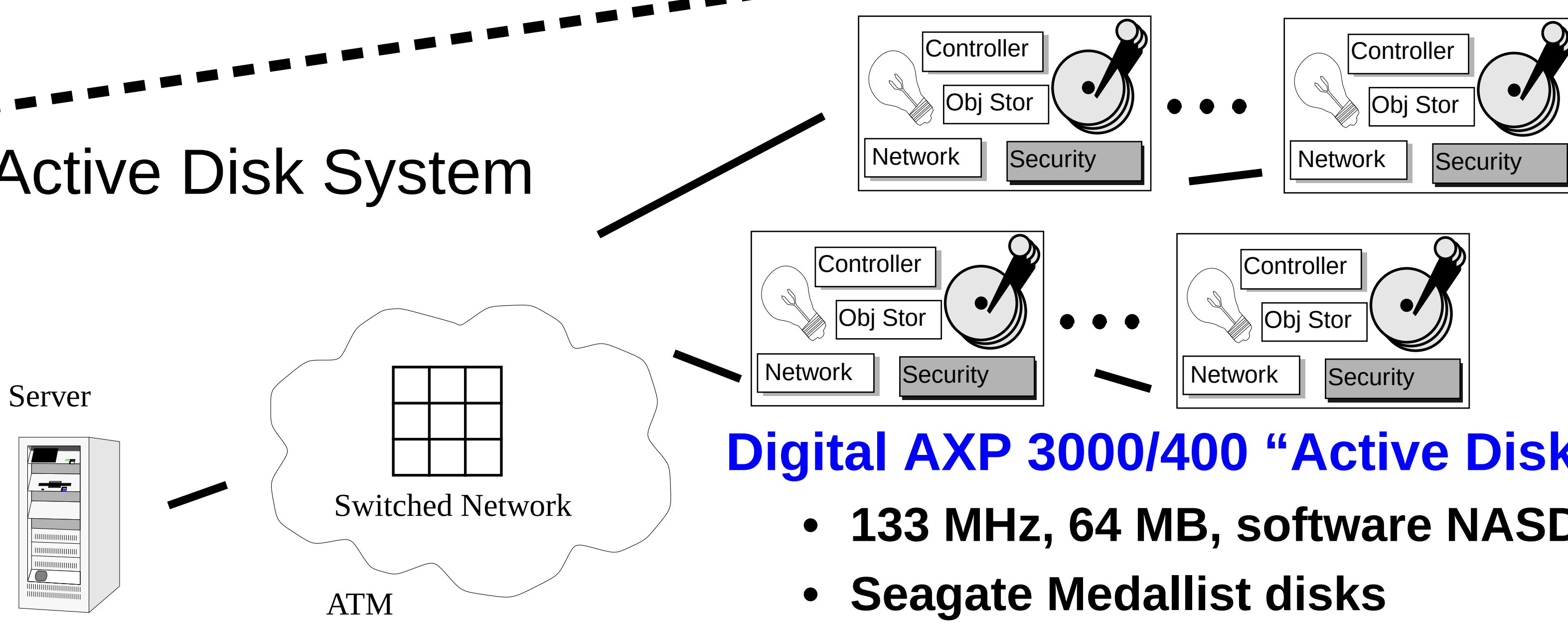
## Traditional System




### Digital AlphaServer 500/500

- **500 MHz, 256 MB memory**
- **Seagate Cheetah disks**
- **4.5 GB, 11.2 MB/s**

## Active Disk System




### Digital AXP 3000/400 “Active Disks”

- **133 MHz, 64 MB, software NASD**
- **Seagate Medallist disks**
- **4.1 GB, 6.5MB/s**

# Data Mining & Multimedia

## Data Mining - association rules [Agrawal95]

- frequent sets summary counts
- milk & bread => cheese

## Database - nearest neighbor search

- *k* records closest to input record
- with large number of attributes, reduces to scan

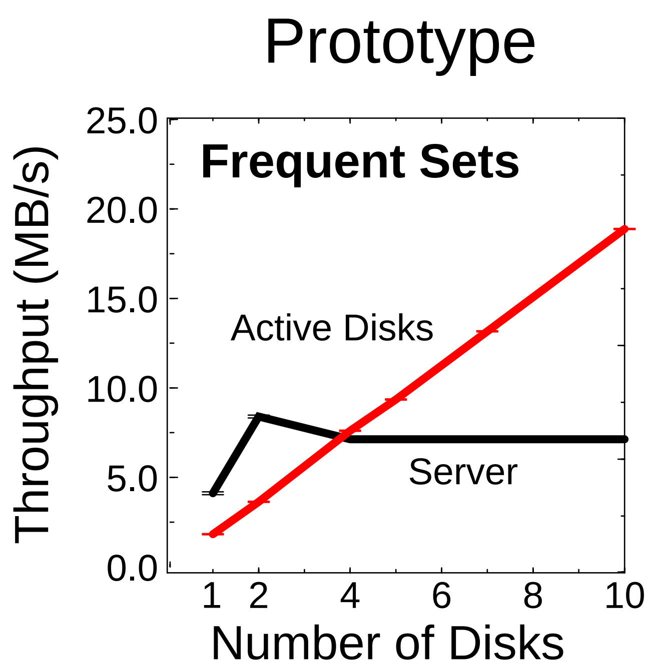
## Multimedia - edge detection [Smith95]

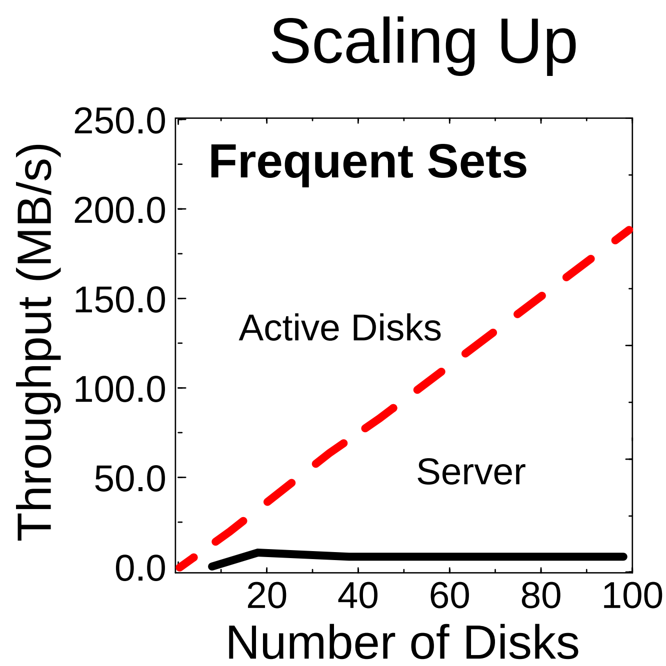
- detect edges in an image

## Multimedia - image registration [Welling97]

- find rotation and translation from reference image

# Data Mining & Multimedia



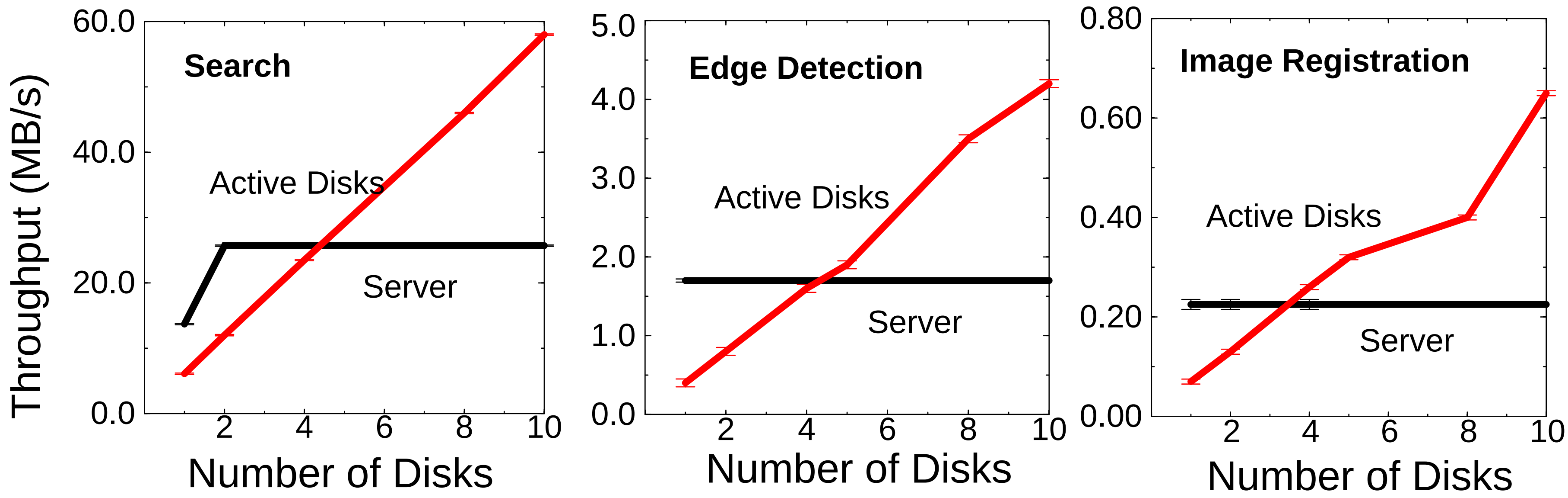




## Prototype performance

- **factor of 2.5x with Active Disks**
- **scalable in a more realistic, larger system**

# Performance with Active Disks

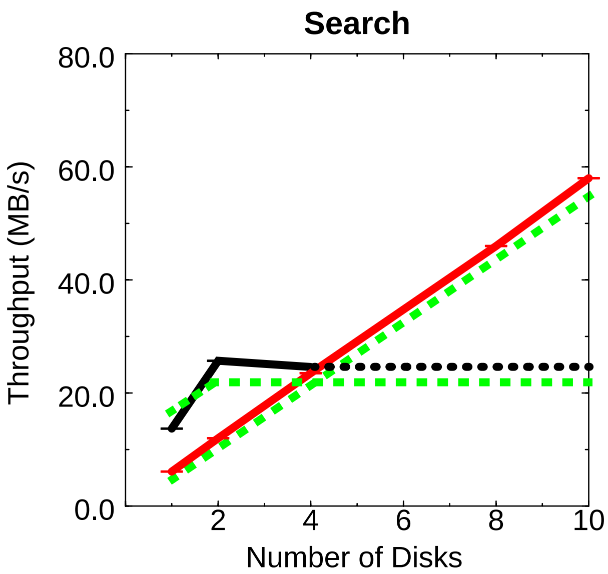
| application | input | computation (inst/byte) | throughput (MB/s) | memory (KB) | selectivity (factor) | bandwidth (KB/s) |
|---|---|---|---|---|---|---|
| Search | k=10 | 7 | 28.6 | 72 | 80,500 | 0.4 |
| Frequent Sets | s=0.25% | 16 | 12.5 | 620 | 15,000 | 0.8 |
| Edge Detection | t=75 | 303 | 0.67 | 1776 | 110 | 6.1 |
| Image Registration | - | 4740 | 0.04 | 672 | 180 | 0.2 |

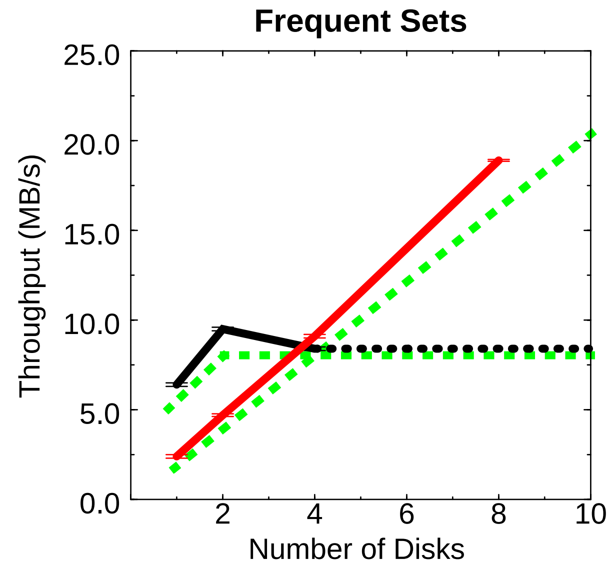


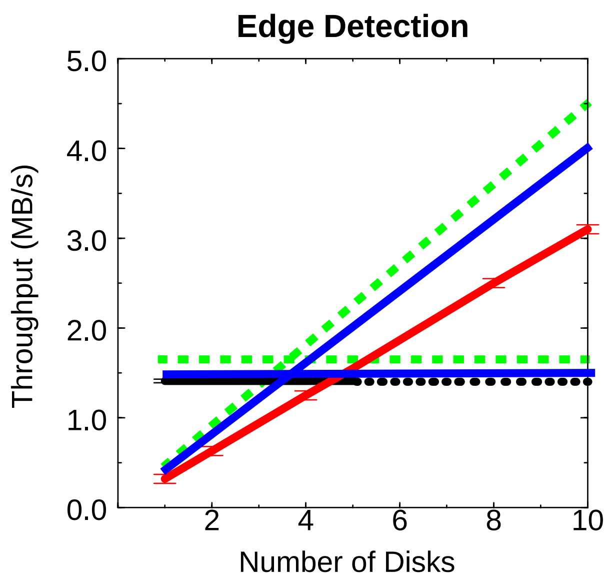

## Scalable performance

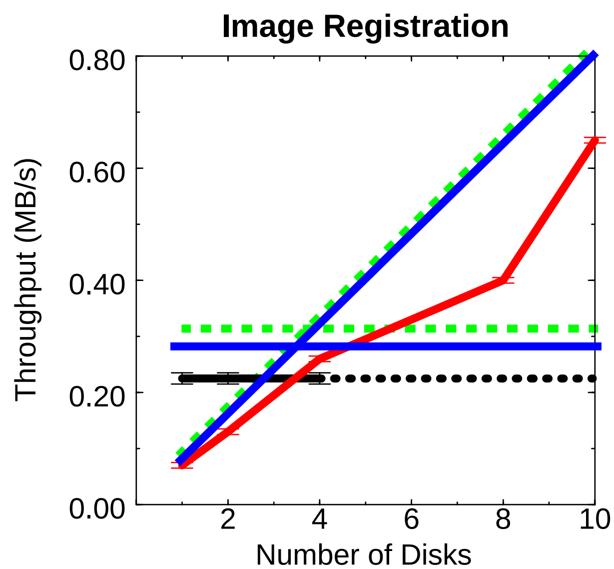
- **crossover at four disks - “technology gap”**
- **cycles/byte => throughput**
- **selectivity => network bottleneck**

# Model Validation



# Database Systems

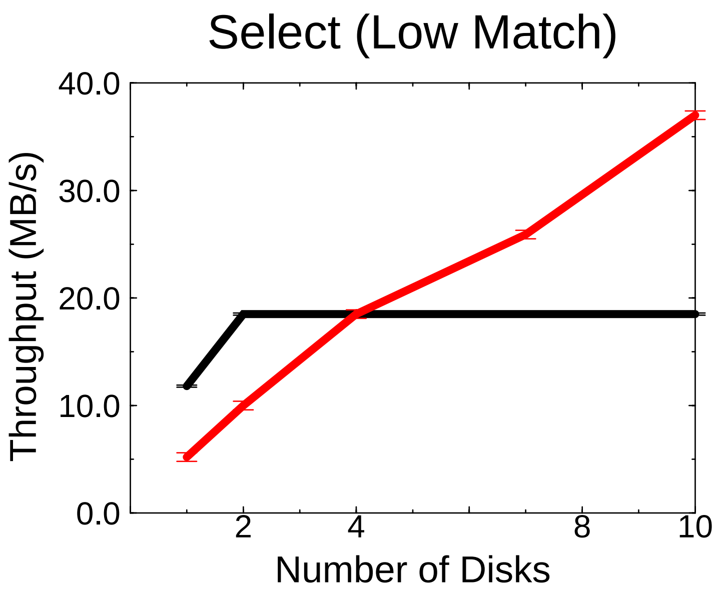
## Basic Operations

- **select - scan**
- **project - scan & sort**
- **join - scan & hash-join**

## Workload

- **TPC-D decision support**
  - **large data, scale factor of 300 GB uses 520 disks**
  - **ad-hoc queries**
  - **high-selectivity, “summary” questions**

# Active PostgreSQL Select




## Experimental setup

- database is PostgreSQL 6.5
- server is 500 MHz Alpha, 256 MB
- disks are Seagate Cheetahs
- vs. *n* Active Disks
  - 133 MHz Alpha, 64 MB
  - Digital UNIX 3.2g
- ATM networking vs. Ultra SCSI

## performance results

- SQL `select` operation (selectivity = 52)
- interconnect limited
- scalable Active Disk performance



# Database - Aggregation (Project)

| l_return | sum_revenue | sum_qty |
|---|---|---|
| A | 39599.7 | 29 |
| R | 67936.6 | 71 |

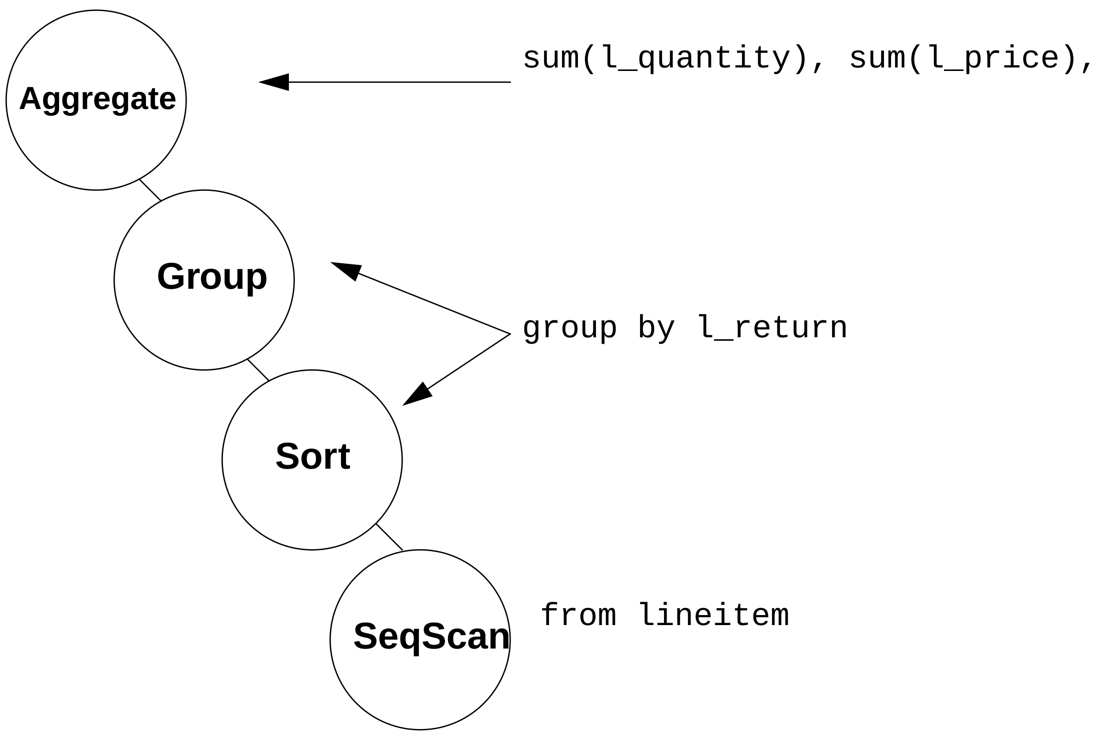
```
select sum(l_price), sum(l_qty)
from lineitem
group by l_return
```

relation S

| l_orderkey | l_shipdate | l_qty | l_price | l_return |
|---|---|---|---|---|
| 1730 | 01-25-93 | 6 | 11051.6 | A |
| 3713 | 04-12-96 | 32 | 29600.3 | R |
| 7010 | 10-05-98 | 23 | 29356.3 | A |
| ... | | | | |
| 32742 | 05-05-95 | 8 | 9281.9 | R |
| 36070 | 11-27-98 | 31 | 34167.9 | R |

# Database - Aggregation II

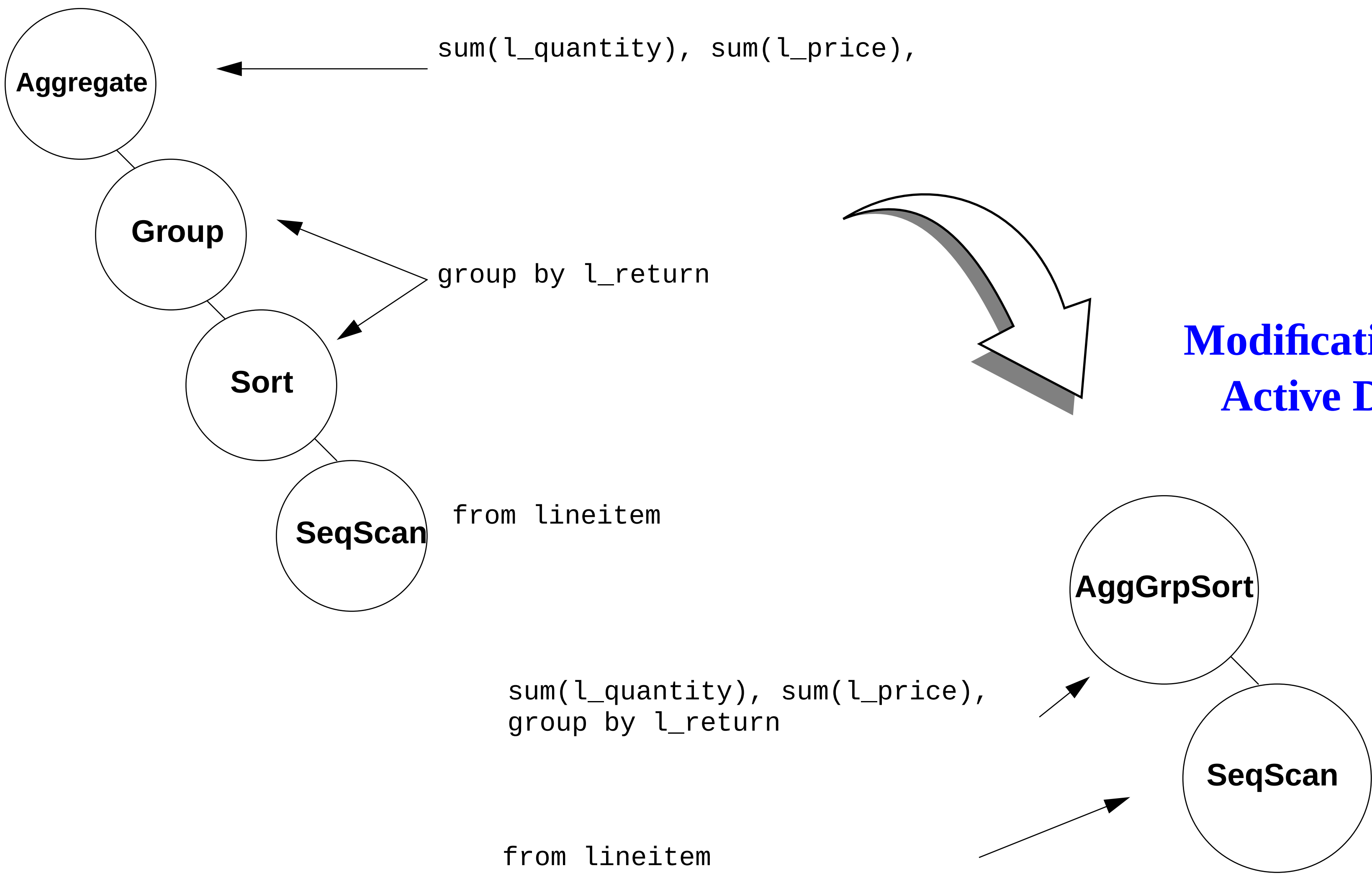
**Query Plan** **Query Text**



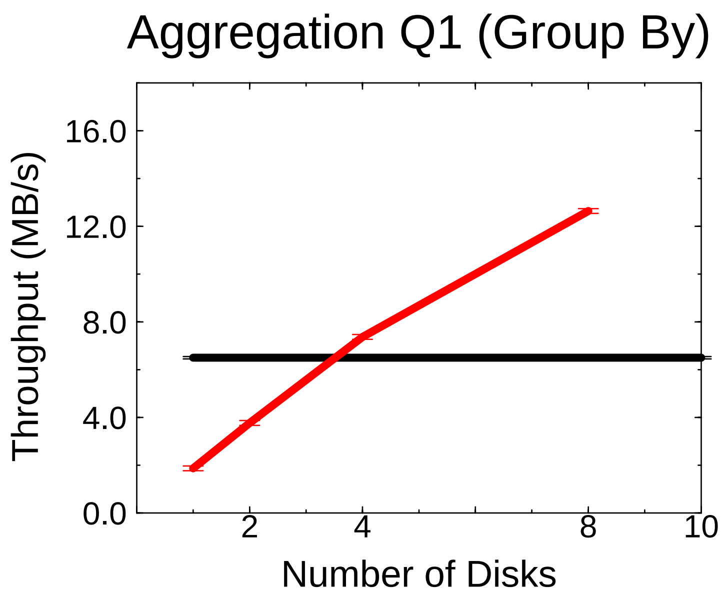
# Database - Aggregation II

## Query Plan

## Query Text



# Active PostgreSQL Aggregation




## Algorithm

- **replacement selection sort**
- **maintain sorted heap in memory**
- **combine (aggregate) records when keys match exactly**

## Benefits

- **memory requirements determined by *output* size**
- **longer average run length**
- **easy to make *adaptive***

## Disadvantage

- **poor memory behavior vs. qsort**

## performance results

- **SQL `sum()...group by` operation (selectivity = 650)**
- **cycles/byte = 32, cpu limited**

# Database - Join

| l_return | sum_revenue | sum_qty |
|---|---|---|
| A | 40407.9 | 29 |
| R | 34167.9 | 31 |

```
select sum(l_price), sum(l_qty)
from lineitem, part
where p_name like '%green%'
and l_partkey = p_partkey
group by l_return
```

relation R

| p_partkey | p_name | p_brand | p_type |
|---|---|---|---|
| 2593 | green car | vw | 11 |
| 5059 | red boat | fast | 29 |
| 1098 | green tree | pine | 35 |
| ... | | | |
| 0412 | blue sky | clear | 92 |
| 5692 | red river | dirty | 34 |

relation S

| l_orderkey | l_partkey | l_qty | l_price | l_return |
|---|---|---|---|---|
| 1730 | 2593 | 6 | 11051.6 | A |
| 3713 | 0412 | 32 | 29600.3 | R |
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# Bloom Join

```
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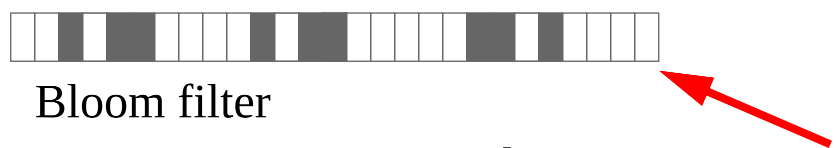

Bloom filter

relation R

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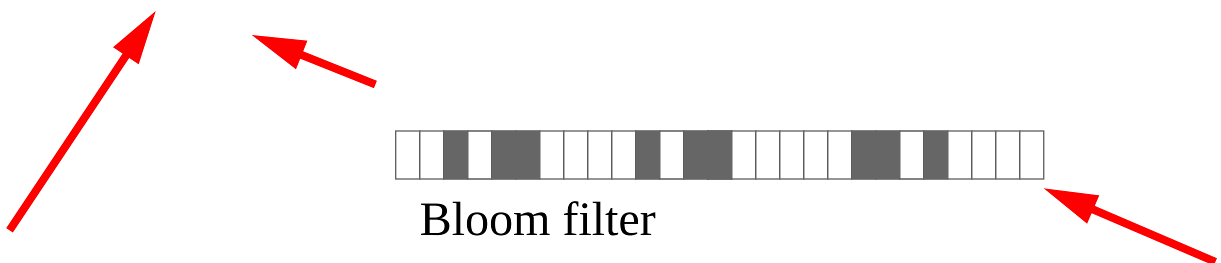

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Bloom filter

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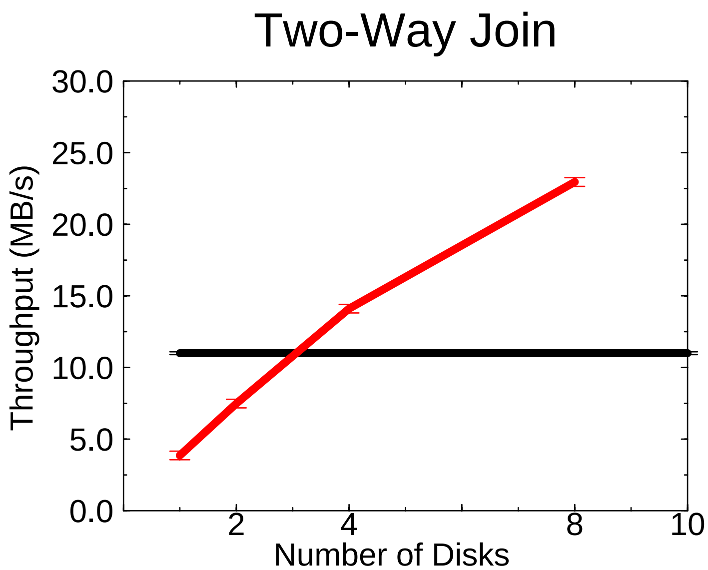
# Active PostgreSQL Join



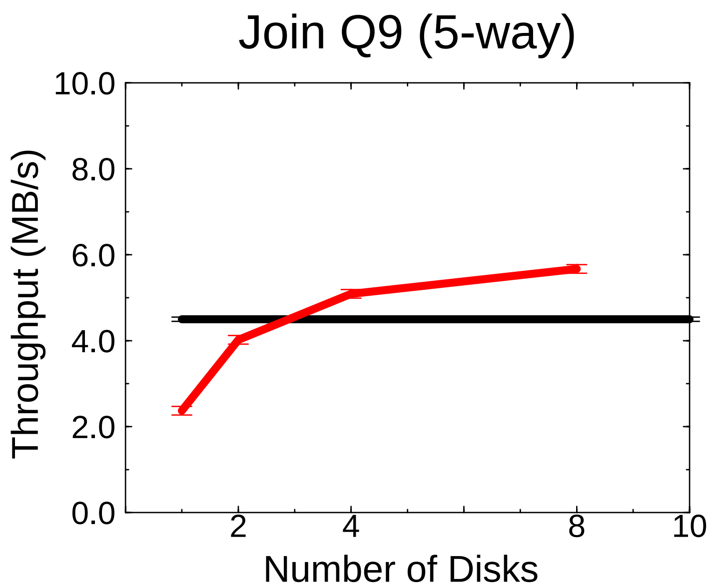

### Algorithm

- read R to host
- create hash table for R
  - generate Bloom filter
- broadcast filter to all disks
- parallel scan at disks
  - semi-join to host
- final join at host

## performance results

- SQL `2-way join` operation (selectivity = 8)
- will eventually be network limited

# Active PostgreSQL Join II

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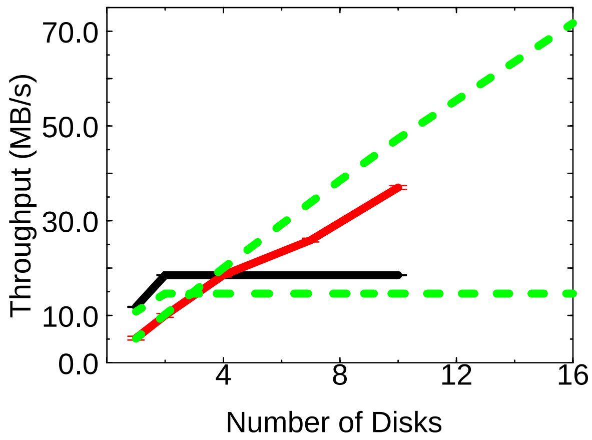
- **server is 500 MHz Alpha, 256 MB**
- **disks are Seagate Cheetahs**
- **vs. *n* Active Disks**
  - **133 MHz Alpha, 64 MB**
  - **Digital UNIX 3.2g**
- **ATM networking vs. Ultra SCSI**

## performance results

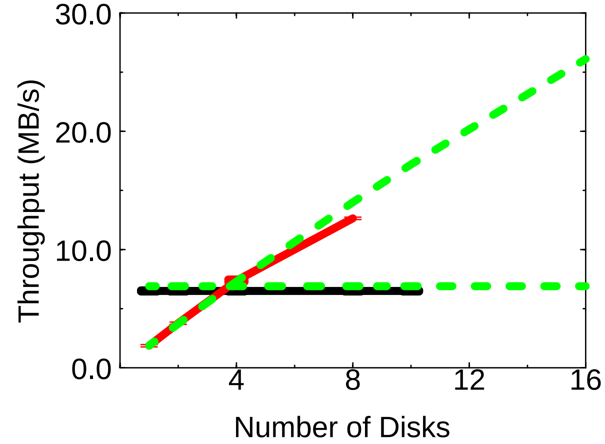
- **SQL `5-way join` operation**
- **large serial fraction, Amdahl's Law kicks in**

# Model Validation (Database)

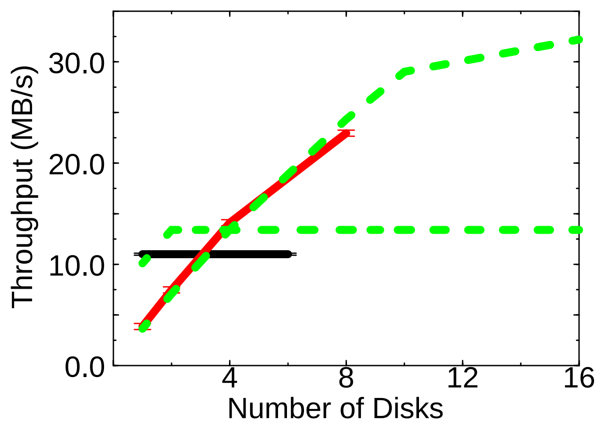
Select Q1 (5% Match)



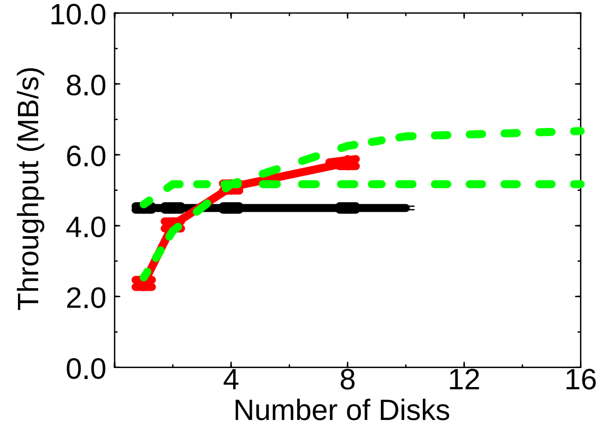

Aggregation Q1 (Group By)




Two-Way Join




Join Q9



# Database - Summary

## Active PostgreSQL Prototype

| Query | Bottleneck | Traditional (seconds) | Active Disks (seconds) | Improvement |
|---|---|---|---|---|
| Q1 | computation | 76.0 | 38.0 | **100%** |
| Q5 | serial fraction | 219.0 | 186.5 | **17%** |
| Q6 | interconnect | 27.2 | 17.0 | **60%** |
| Q9 | serial fraction | 95.0 | 85.4 | **11%** |

## Measured performance

- **four most expensive of the 17 TPC-D queries**
- **compares eight disk systems**
- **PostgreSQL 6.5 with Active Disk modifications**



# Database - Extrapolation

## Estimated Speedup on Digital 8400 (TPC-D, May 1998)

| Query | Bottleneck | Traditional (seconds) | Active Disks (seconds) | Improvement |
|---|---|---|---|---|
| Q1 | computation | 4,357.1 | *307.7* | ***1,320%*** |
| Q5 | serial fraction | 1988.2 | *1,470.8* | ***35%*** |
| Q6 | interconnect | 63.1 | *6.1* | ***900%*** |
| Q9 | serial fraction | 2710.8 | *2,232.1* | ***22%*** |

## Predicted performance

- **comparison of Digital 8400 with 520 traditional disks**
- **vs. the same system with 520 Active Disks**

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| Other Qs | | *assume unchanged* | | |
| Overall | | 18,619.5 | *13,517.0* | ***38%*** |

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# Database - Extrapolation

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| Overall | | 18,619.5 | *13,517.0* | *38%* |
| Cost | | $2,649,262 | *$3,034,045* | *15%* |

## Predicted performance

- **comparison of Digital 8400 with 520 traditional disks**
- **vs. the same system with 520 Active Disks**
- **overall cost increase of about 15%**
  - **- assuming an Active Disk costs *twice* a traditional disk**

# Outline

**Motivation**

**Computation in Storage**

**Performance Model**

**Applications & Prototype**

**Drive-Specific Functionality**

**Related Work**

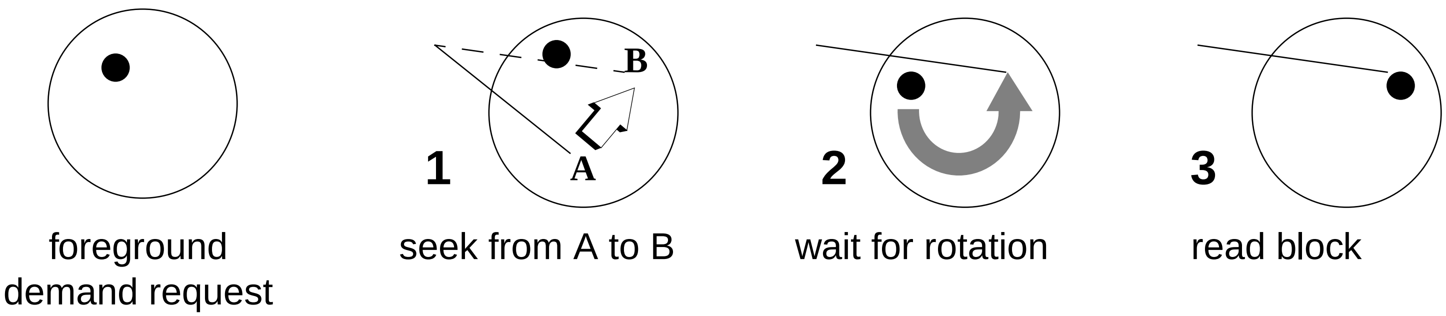
**Contributions & Future Work**

# Additional Functionality

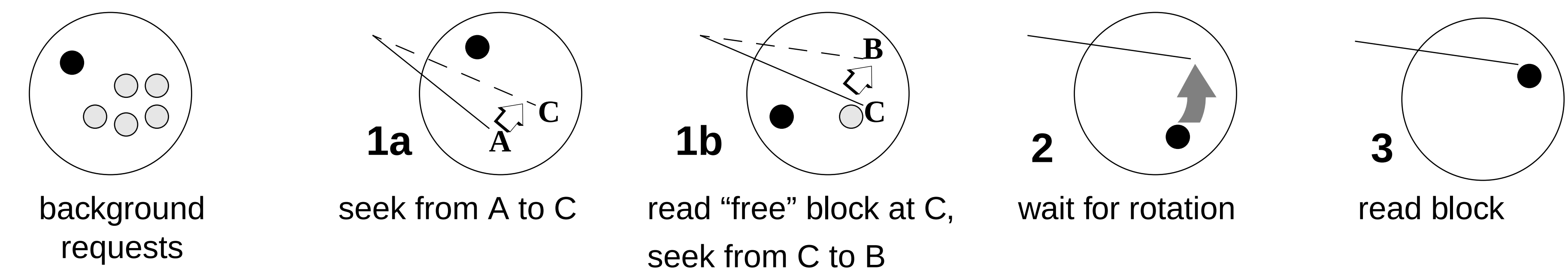
## Data Mining for Free

- process sequential workload during “idle” time in OLTP
- allows e.g. data mining on an OLTP system

## Action in Today’s Disk Drive

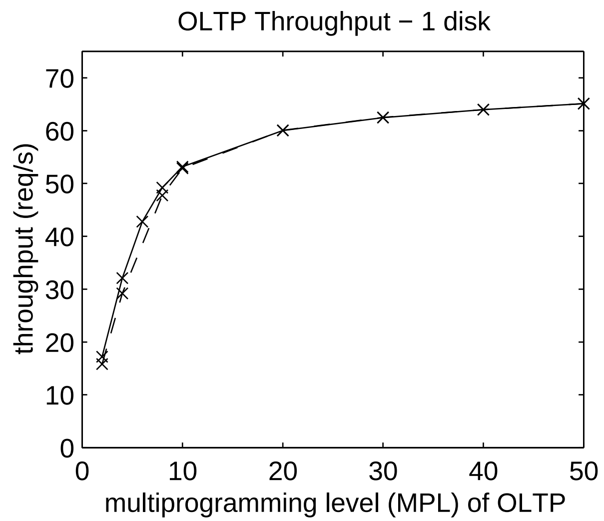


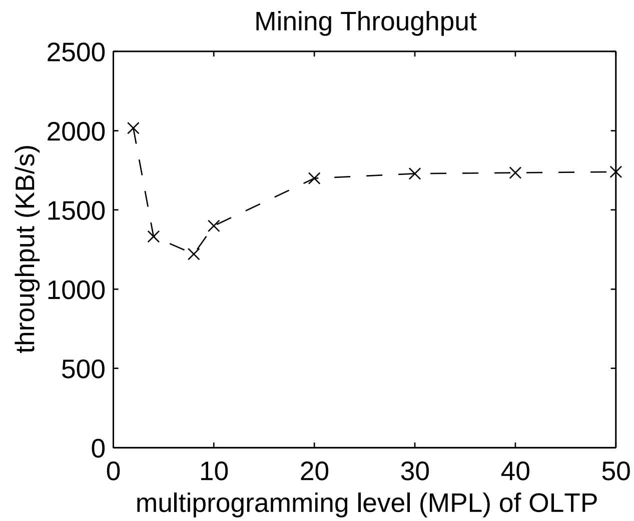

## Modified Action With “Free” Block Scheduling

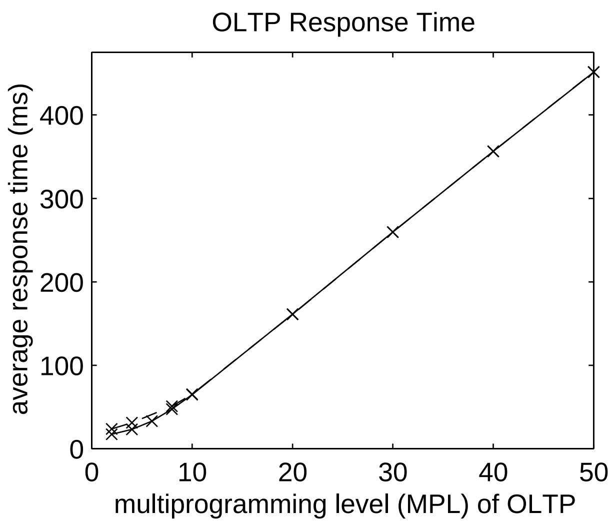


# Data Mining for Free

- **combine background and "free" blocks**




## Integrated scheduling

- **possible only at drives**
- **combines application-level and disk-level information**
- **achieves 30% of the drives sequential band-width "for free"**

# Outline

**Motivation**

**Computation in Storage**

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# Related Work

## Database Machines (CASSM, RAP, Gamma)

- today's advantages - higher disk bandwidth, parallelism
- general-purpose programmability
- parallel databases (Teradata, Tandem, Oracle, IBM)
- CAFS and SCAFS search accelerator (ICL, Fujitsu)

## Parallel Programming

- automatic data parallelism (HPF), task parallelism (Fx)
- parallel I/O (Kotz, IBM, Intel)

## Parallel Database Operations

- scan [Su75, Ozkarahan75, DeWitt81, ...]
- sort [Knuth73, Salzberg90, DeWitt91, Blelloch97, ...]
- hash-join [Kitsuregawa83, DeWitt85, ...]

# Related Work - “Smart Disks”

## Intelligent Disks (Berkeley)

- **SMP database functions [Keeton98]**
- **analytic model, large speedups for join and sort (!)**
- **different architecture - *everything* is iDisks**
- **disk layout [Wang98], write optimizations**

## Programming Model (Santa Barbara/Maryland)

- **select, sort, image processing via extended SCSI [Acharya98]**
- **simulation comparisons among Active Disks, Clusters, SMPs**
- **focus on network bottlenecks**

## SmartSTOR (Berkeley/IBM)

- **analysis of TPC-D, significant benefits possible (!)**
- **suggest using one processor for multiple disks**
- **“simple” functions have limited benefits**



# Contributions

## Exploit technology trends

- "excess" cycles on individual disk drives
- large systems => lots of disks => lots of power

## Analytic

- performance model - predicts within 25%
- algorithms & query optimizer - map to Active Disk functions

## Prototype

- data mining & multimedia
  - 2.5x in prototype, scale to 10x
- database with TPC-D benchmark
  - 20% to 2.5x in prototype, extrapolate 35% to 15x in larger system
- changed ~2% of database code, run ~5% of code at drives

## Novel functionality

- data mining for free - close to 30% bandwidth "for free"

## Conclusion - lots of potential *and* realistically attainable

# Detail Slides

# Amdahl's Law

$$serial = S$$

$$parallel = \frac{(1 - p) \cdot S + \frac{p \cdot S}{n}}{S}$$

## Speedup in a Parallel System

- ***p*** **is parallel fraction**
- ***(1 - p)*** **serial fraction is not improved**



# Database - Select

| l_orderkey | l_shipdate | l_qty | l_price |
|---|---|---|---|
| 7010 | 10-05-98 | 23 | 29356.3 |
| 36070 | 11-27-98 | 31 | 34167.9 |

```
select * from lineitem
where l_shipdate > '01-01-1998'
```

relation S

| l_orderkey | l_shipdate | l_qty | l_price | l_disc |
|---|---|---|---|---|
| 1730 | 01-25-93 | 6 | 11051.6 | 0.02 |
| 3713 | 04-12-96 | 32 | 29600.3 | 0.07 |
| 7010 | 10-05-98 | 23 | 29356.3 | 0.09 |
| ... | | | | |
| 32742 | 05-05-95 | 8 | 9281.9 | 0.01 |
| 36070 | 11-27-98 | 31 | 34167.9 | 0.04 |

# Bloom Join

## Use only Bloom filter at disks

- **semi-join only, final join at host**
- **fixed-size bit vectors - memory size O(1)!**

| **Query** | **Join** | **Size of Bloom filter** | | | | | **Keys** | **Table** |
|---|---|---|---|---|---|---|---|---|
| | | 128 bits | 8 kilobytes | 64 kilobytes | 1 megabyte | ideal | MB | GB |
| | | | | | | | | |
| Q3 | 1.1 | 1.00 | 0.33 | 0.33 | 0.33 | 0.21 | 12.4 | 4.2 |
| Q5 | 4.1 | 0.90 | 0.22 | 0.22 | 0.22 | 0.22 | 0.9 | 0.3 |
| Q9 | 1.1 | 1.00 | 0.11 | 0.11 | 0.11 | 0.05 | 4.0 | 4.7 |
| Q10 | 2.1 | - | 0.33 | 0.21 | 0.21 | 0.08 | 21.9 | 28.6 |

## Memory size required at each disk

- **from TPC-D queries at 100 GB scale factor**
- **using a single hash function for all tables and keys**

# Outline

Motivation

Computation in Storage

Performance Model

Applications & Prototype

Software Structure

Drive-Specific Functionality

Related Work

Contributions & Future Work

# Database Primitives

## Scan

- evaluate predicate, return matching records
- low memory requirement

## Join

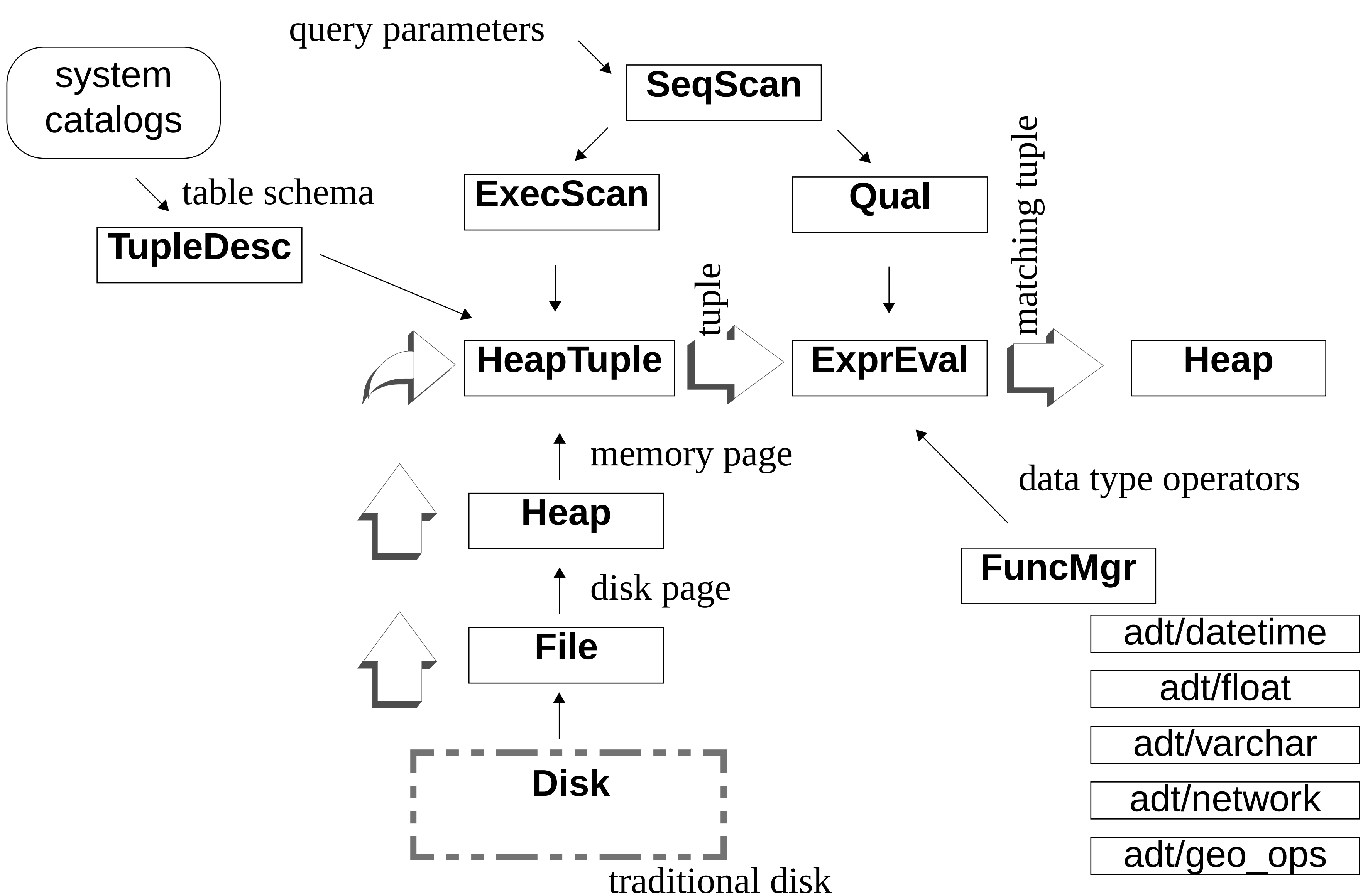
- identify matching records in semijoin
- via direct table lookup
- or Bloom filter, when memory is limited

## Aggregate/Sort

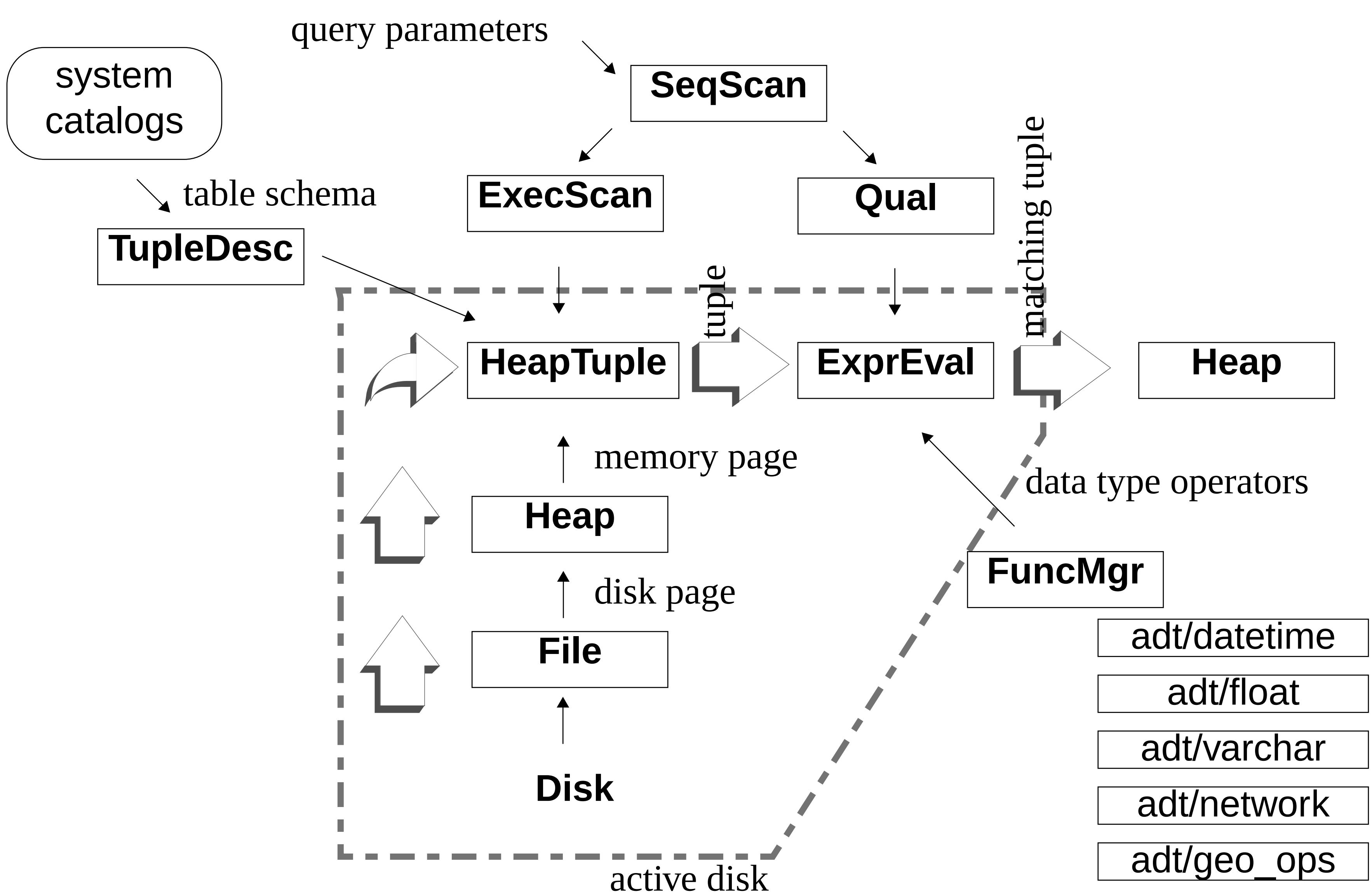
- replacement selection with record merging
- memory size proportional to result, not input
- runs of length *2m* when used in full mergesort



# Execute Node

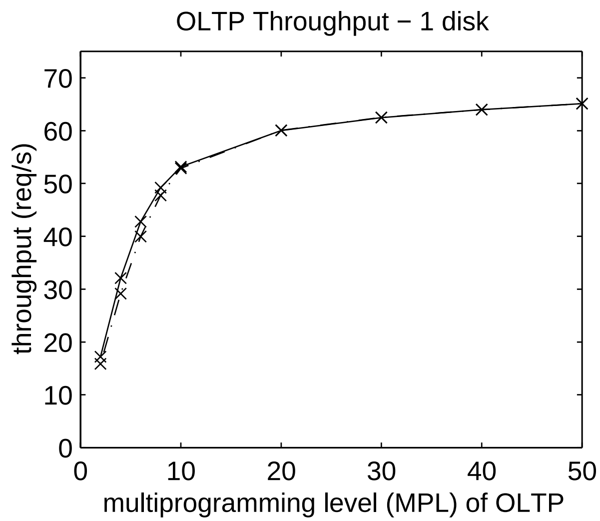


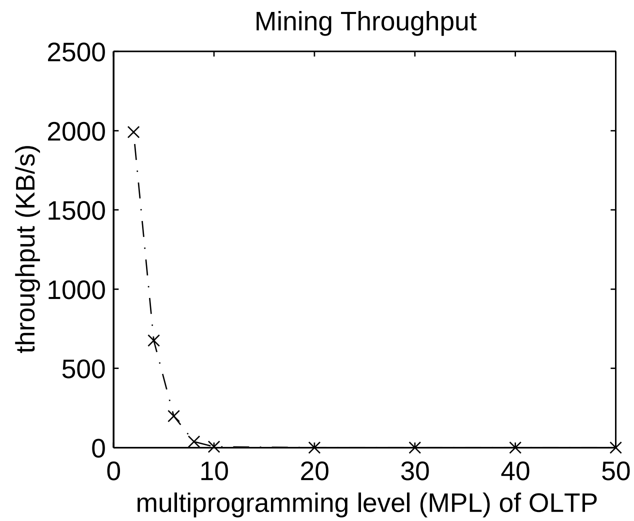
# Active Disk Structure

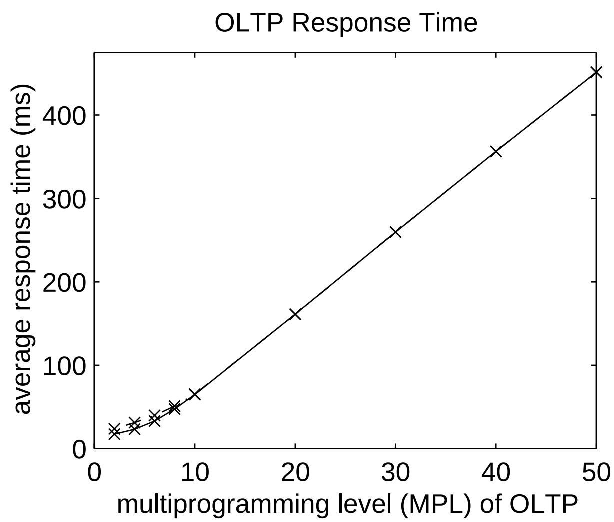


# Data Mining for Free

- **read background blocks only when queue is empty**



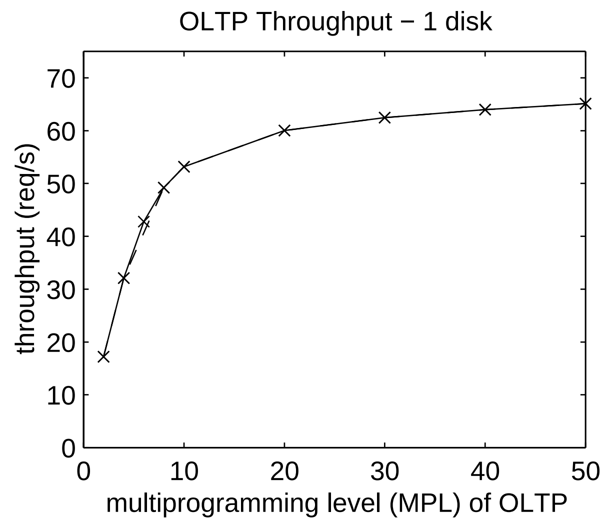



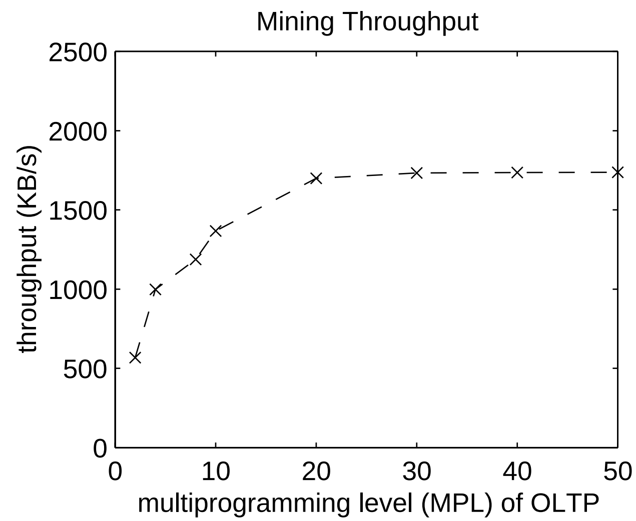

## Background scheduling

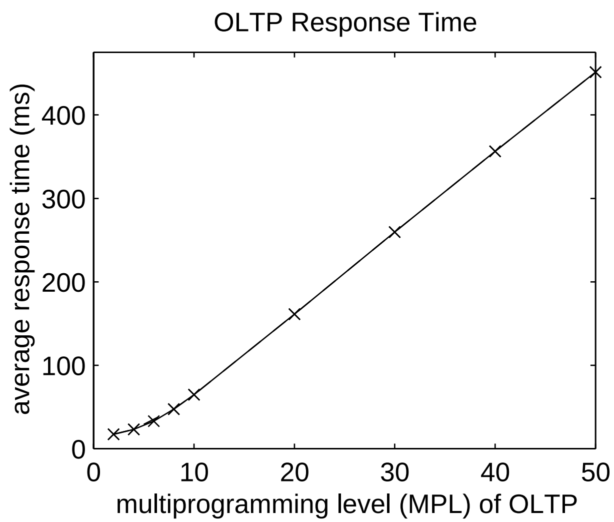
- **vary multiprogramming level - total number of pending requests**
- **background forced out at high foreground load**
- **up to 30% response time impact at low load**

# Data Mining for Free

- **read background blocks only when completely "free"**



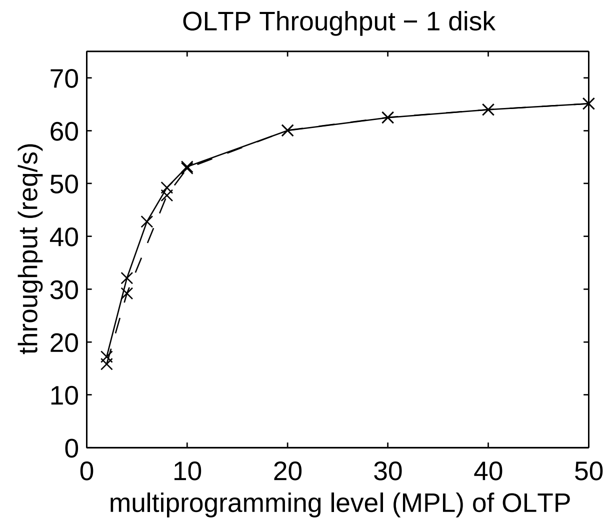



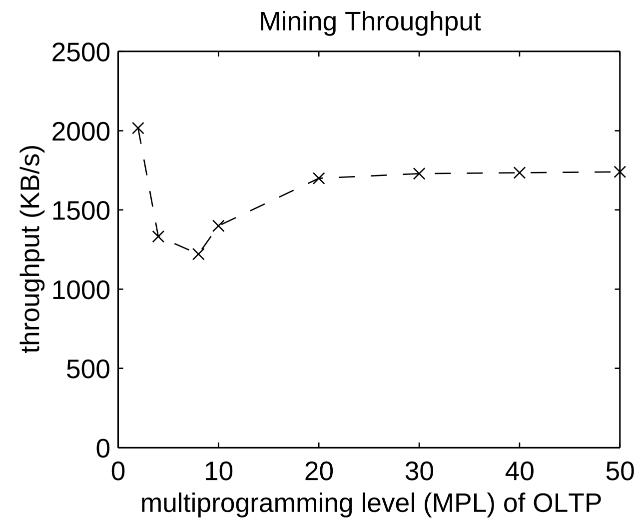

## Free block scheduling

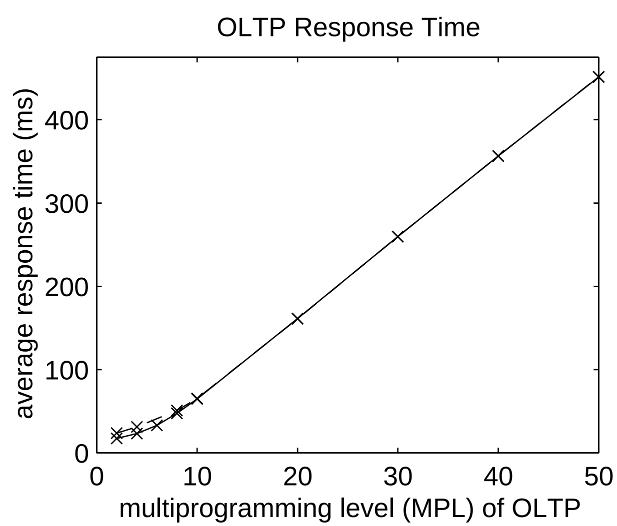
- **opportunistic read**
- **constant background bandwidth, even at highest loads**
- **no impact on foreground respond time**

# Data Mining for Free

- **combine background and “free” blocks**




## Integrated scheduling

- **possible only at drives**
- **combines application-level and disk-level information**
- **achieves 30% of the drives sequential band-width “for free”**

# Extra Slides

# Why Isn't This Parallel Programming?

## It is

- parallel cores
- distributed computation
- serial portion needs to be small

## Disks are different

- must protect the data, can't "just reboot"
- must continue to serve demand requests
- memory/CPU ratios driven by cost, reliability, volume
- come in boxes of ten
- *basic advantage* - compute close to the data

## *Opportunistically* use this power

- e.g. data mining possible on an OLTP system
- ok to "waste" the power if it can't be used

# Application Characteristics

## Critical properties for Active Disk performance

- **cycles/byte => maximum throughput**
- **memory footprint**
- **selectivity => network bandwidth**

| **application** | **input** | **computation** (instr/byte) | **throughput** (MB/s) | **memory** (KB) | **selectivity** (factor) | **bandwidth** (KB/s) |
|---|---|---|---|---|---|---|
| Select | m=1% | 7 | 28.6 | - | 100 | 290 |
| Search | k=10 | 7 | 28.6 | 72 | 80,500 | 0.4 |
| Frequent Sets | s=0.25% | 16 | 12.5 | 620 | 15,000 | 0.8 |
| Edge Detection | t=75 | 303 | 0.67 | 1776 | 110 | 6.1 |
| Image Registration | - | 4740* | 0.04 | 672 | 180 | 0.2 |
| | | | | | | |
| Select | m=20% | 7 | 28.6 | - | 5 | 5,700 |
| Frequent Sets | s=0.025% | 16 | 12.5 | 2,000 | 14,000 | 0.9 |
| Edge Detection | t=20 | 394 | 0.51 | 1750 | 3 | 170 |

# Sorts

## Local Sort Phase

- **replacement selection in Active Disk memory**
  **process as data comes off the disk**
- **build sorted runs of average size *2m***
- **can easily adapt to changes in available memory**

## Local Merge Phase

- **perform sub-merges at disks**
  **less runs to process at host**
- **also adaptable to changes in memory**

## Global Merge Phase

- **moves all data to the host and back**

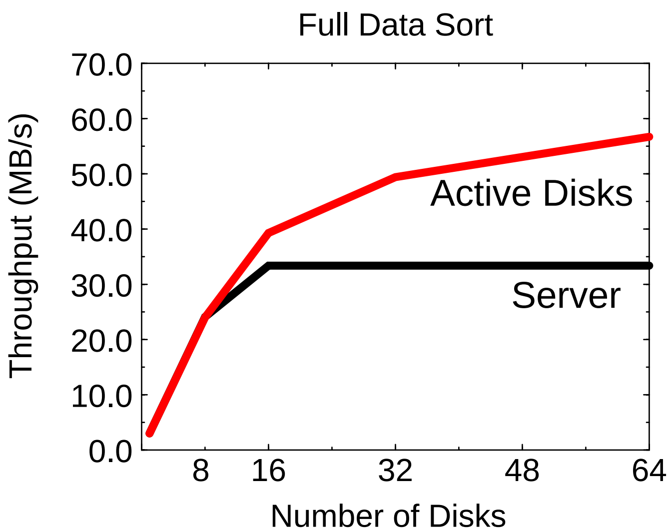
## Optimizations

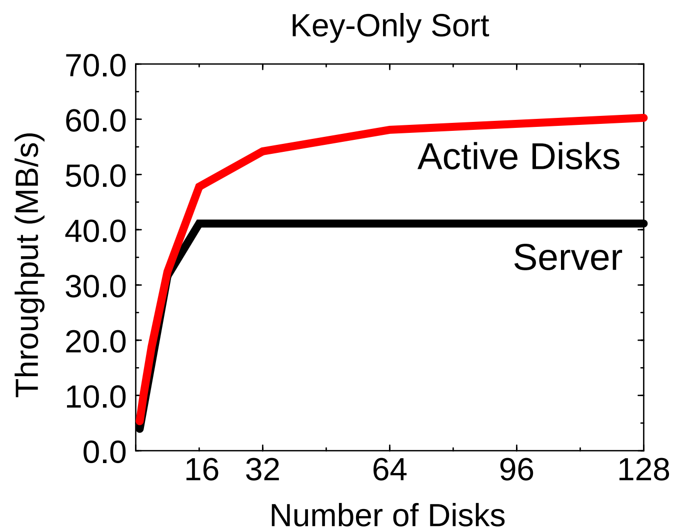
- **duplicate removal, aggregation lower requirements**
  **memory required only for result, not source relations**

## Bottleneck is the Network - the Data *Must* Move Once

- **so goal is optimal utilization of links**

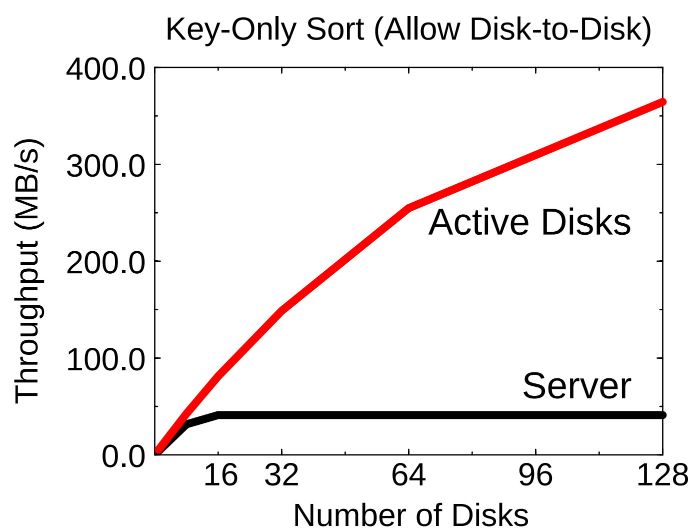
# Sort Performance




## Network is the bottleneck

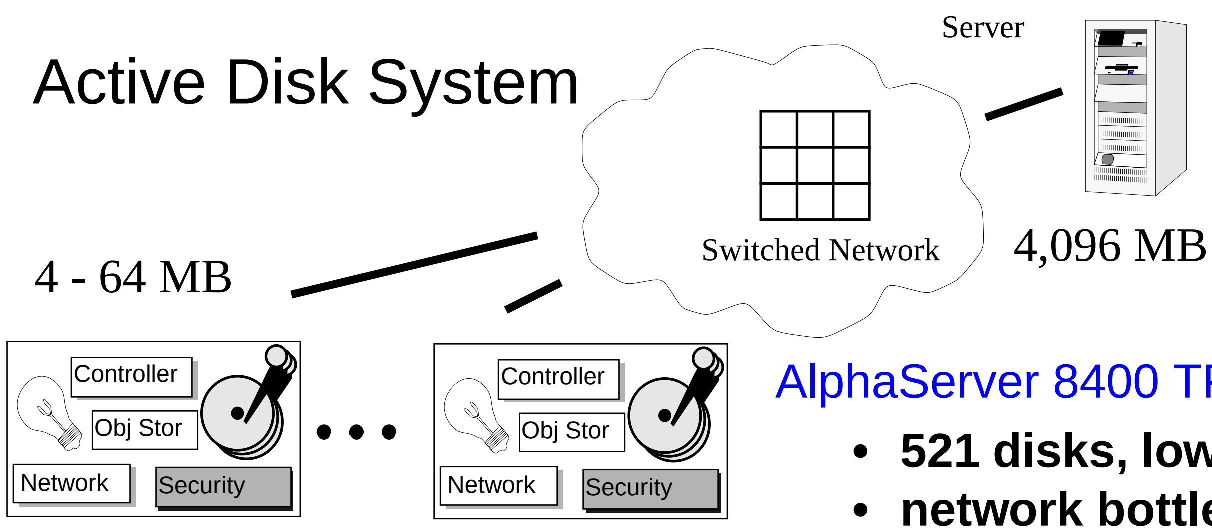
- **Active Disks benefit from reduced interconnect traffic**
- **using key-only sort improves both systems**
- **with direct disk to disk transfers, data *never* goes to the host**



# Database - Joins

## Size of R determines Active Disk partitioning

- **if |R| << |S|    (R is the inner, smaller relation)**
  - **- and |R| < |*Active Disk* memory|**
    - **embarassingly parallel, linear speedup**
  - **- and |R| < |*Server* memory|**
    - **retain portion of R at each disk, and “assist” Server**
- **if |R| ~ |S| and |R| > |*Server* memory|**
  - **process R in parallel, minimize network traffic**
- **pre-join scan on S and R is always a win**
  - **reduces interconnect traffic**



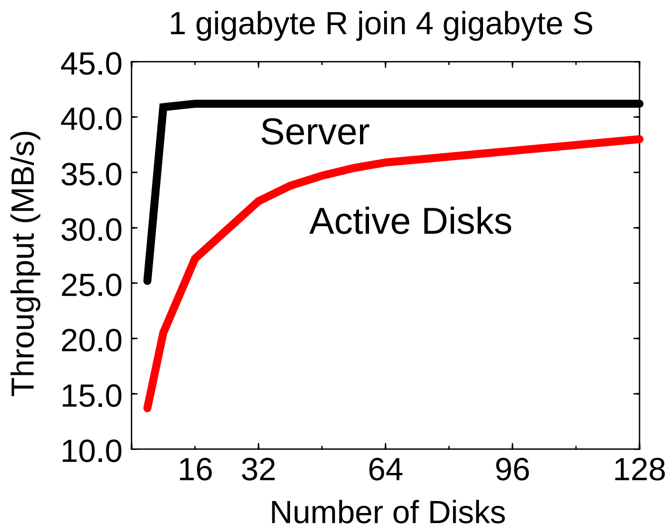

### *Assumptions*

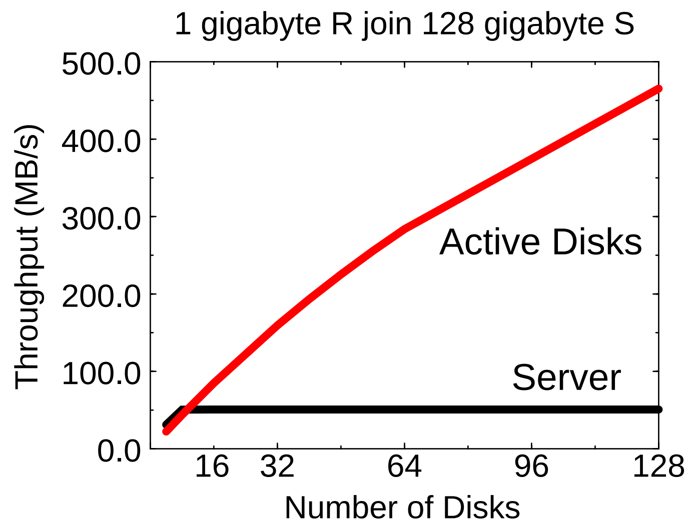
- **non-indexed keys**
- **not partition keys**
- **large S (multi-GB)**
  **=>      many disks**

AlphaServer 8400 TPC-D

- **521 disks, low CPU cost**
- **network bottlenecked**

# Join Performance




## benefits from reduced interconnect traffic

- determinant is relative size of inner and outer relations
- savings in network transfer
- vs. multiple passes at disks

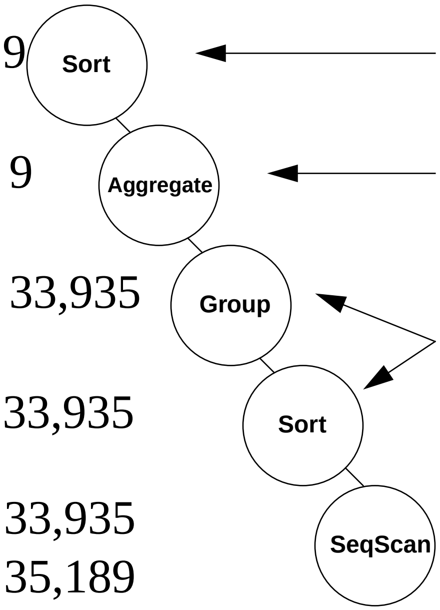
# Database - TPC-D Query 1

## Data Reduction

| | |
|---|---|
| Sort | 9 -> 9 |
| Aggr | 33,935 -> 9 |
| Group | 33,935 -> 33,935 |
| Sort | 33,935 -> 33,935 |
| Qual | 35,189 -> 33,935 |
| Scan | 126,440 -> 35,189 |

126,440 KB (15,805 pages) on disk

## Query Plan




## Query Text

```
order by l_returnflag, l_linestatus

sum(l_quantity), sum(l_price),
sum(l_price*(1-l_disc)),
sum(l_price*(1-l_disc)*(1+l_tax)),
avg(l_quantity), avg(l_price),
avg(l_disc), count(*)

group by l_returnflag, l_linestatus

where l_shipdate <= '1998-09-02'

select l_returnflag, l_linestatus,

from lineitem
```

input

output

## Query Result

```
l_rf|l_ls|sum_qty|sum_base_price|sum_disc_price|    sum_charge|avg_qty|   price| disc| count
----+----+-------+--------------+--------------+--------------+-------+--------+-----+------
A   |F   |3773034| 5319329289.67| 5053976845.78| 5256336547.67| 25.509|35964.01|0.049|147907
N   |F   | 100245|  141459686.10|  134380852.77|  139710306.87| 25.625|36160.45|0.050|  3912
N   |O   |7464940|10518546073.97| 9992072944.46|10392414192.06| 25.541|35990.12|0.050|292262
R   |F   |3779140| 5328886172.98| 5062370635.93| 5265431221.82| 25.548|36025.46|0.050|147920
(4 rows)
```

## Data Reduction for Sequential Scan and Aggregation

| Query | Input Data (KB) | SeqScan Result (KB) | SeqScan Savings (selectivity) | Aggregate Result (bytes) | Aggregate Savings (selectivity) |
|---|---|---|---|---|---|
| Q1 | 126,440 | 34,687 | 3.6 | 240 | 147,997.9 |
| Q4 | 29,272 | 86 | 340.4 | 80 | 1100.8 |
| Q6 | 126,440 | 177 | 714.4 | 8 | 22,656.0 |

### Input Table

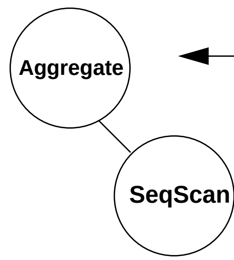
| l_okey | l_quantity | l_price | l_disc | l_tax | l_rf | l_ls | l_shipdate | l_commitdate | l_receiptdate | l_shipmode | l_comment |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1730 | 6 | 11051.58 | 0.02 | 0 | N | O | 09-02-1998 | 10-10-1998 | 09-13-1998 | TRUCK | wSRnnCx2 |
| 3713 | 32 | 29600.32 | 0.07 | 0.03 | N | O | 09-02-1998 | 06-11-1998 | 09-28-1998 | TRUCK | MOgnCO1 |
| 7010 | 23 | 29356.28 | 0.09 | 0.06 | N | O | 09-02-1998 | 08-01-1998 | 09-14-1998 | MAIL | jPNQlx3i |
| 19876 | 4 | 6867.24 | 0.09 | 0.08 | N | O | 09-02-1998 | 09-06-1998 | 09-29-1998 | AIR | 3nRkNn4 |
| 24839 | 8 | 12845.52 | 0.05 | 0.02 | N | O | 09-02-1998 | 10-14-1998 | 09-06-1998 | REG AIR | jlw61g3 |
| 25217 | 10 | 18289.1 | 0.05 | 0.07 | N | O | 09-02-1998 | 08-12-1998 | 09-26-1998 | TRUCK | SQ7xS5 |
| 29348 | 29 | 41688.08 | 0.05 | 0.02 | N | O | 09-02-1998 | 07-04-1998 | 09-18-1998 | FOB | C0NxhzM |
| 32742 | 8 | 9281.92 | 0.01 | 0.03 | N | O | 09-02-1998 | 07-17-1998 | 09-19-1998 | FOB | N3MO1C |
| 36070 | 31 | 34167.89 | 0.04 | 0 | N | O | 09-02-1998 | 07-11-1998 | 09-21-1998 | REG AIR | k10wyR |

[...more...]
(600752 rows)

# Database - Aggregation

**Data Reduction** **Query Plan** **Query Text**

Aggr 43 -> 1




```
select

sum(l_price*l_disc)

where l_shipdate >= '1994-01-01'
and l_shipdate < '1995-01-01'
and l_disc between 0.05 and 0.07
and l_quantity < 24

from lineitem
```

Qual 9,383 -> 43

Scan 126,440 -> 9,383

126,440 KB (15,805 pages) on disk

input

output

**Query Result**

```
revenue
-----------
11450588.04
(1 row)
```

# Database - Partitioning

## How to split operations between host and drives?

## Answer: Use existing query optimizer

- **operation costs**
- **per-table and per-attribute statistics**
- **ok if they are slightly out-of-date, only an estimate**

| Query | Input Data (KB) | Scan Result (KB) | Optimizer Estimate (KB) | Qualifier Result (KB) | Optimizer Estimate (KB) | Aggregate Result (bytes) | Optimizer Estimate (bytes) |
|---|---|---|---|---|---|---|---|
| Q1 | 126,440 | 35,189 | 35,189 | 34,687 | 33,935 | 240 | 9,180 |
| Q4 | 29,272 | 2,343 | 2,343 | 86 | 141 | 80 | 64 |
| Q6 | 126,440 | 9,383 | 9,383 | 177 | 43 | 8 | 8 |

## Move ops to drives if there are sufficient resources

- **if selectivity and parallelism overcome slower CPU**

## Be prepared to revert to host as two-stage algorithm

- **consider the disk as “pre-filtering”**
- **still offloads significant host CPU and interconnect**

# Database - Optimizer Statistics

| starelid | staattnum | staop | stalokey | stahikey |
|---|---|---|---|---|
| 18663 | 1 | 66 | 1 | 600000 |
| 18663 | 2 | 66 | 1 | 20000 |
| 18663 | 3 | 66 | 1 | 1000 |
| 18663 | 4 | 66 | 1 | 7 |
| 18663 | 5 | 295 | 1 | 50 |
| 18663 | 6 | 295 | 901 | 95949.5 |
| 18663 | 7 | 295 | 0 | 0.1 |
| 18663 | 8 | 295 | 0 | 0.08 |
| ***18663*** | ***9*** | ***1049*** | ***A*** | ***R*** |
| 18663 | 10 | 1049 | F | O |
| 18663 | 11 | 1087 | 01-02-1992 | 12-01-1998 |
| 18663 | 12 | 1087 | 01-31-1992 | 10-31-1998 |
| 18663 | 13 | 1087 | 01-08-1992 | 12-30-1998 |
| 18663 | 14 | 1049 | COLLECT COD | TAKE BACK RETURN |
| 18663 | 15 | 1049 | AIR | TRUCK |
| 18663 | 16 | 1049 | 0B6wmAww2Pg | zzzyRPS40ABMRSzmPyCNzA6 |

[...more...]
(61 rows)

## Statistics

estimate 17 output tuples

| attrelid | attname | atttypid | attdisbursion | attlen | attnum |
|---|---|---|---|---|---|
| 18663 | l_orderkey | 23 | 2.33122e-06 | 4 | 1 |
| 18663 | l_partkey | 23 | 1.06588e-05 | 4 | 2 |
| 18663 | l_suppkey | 23 | 0.000213367 | 4 | 3 |
| 18663 | l_linenumber | 23 | 0.0998572 | 4 | 4 |
| 18663 | l_quantity | 701 | 0.00434997 | 8 | 5 |
| 18663 | l_extendedprice | 701 | 2.66427e-06 | 8 | 6 |
| 18663 | l_discount | 701 | 0.0247805 | 8 | 7 |
| 18663 | l_tax | 701 | 0.0321099 | 8 | 8 |
| ***18663*** | ***l_returnflag*** | ***1042*** | ***0.307469*** | ***-1*** | ***9*** |
| 18663 | l_linestatus | 1042 | 0.300911 | -1 | 10 |
| 18663 | l_shipdate | 1082 | 8.94076e-05 | 4 | 11 |
| 18663 | l_commitdate | 1082 | 8.33926e-05 | 4 | 12 |
| 18663 | l_receiptdate | 1082 | 8.90733e-05 | 4 | 13 |
| 18663 | l_shipinstruct | 1042 | 0.100238 | -1 | 14 |
| 18663 | l_shipmode | 1042 | 0.0451101 | -1 | 15 |
| 18663 | l_comment | 1042 | 0 | -1 | 16 |

[...more...]
(572 rows)

## Attributes

estimate 4 output tuples

# Active PostgreSQL - Code Changes

| Module | Original | | Modified Host (New & Changed) | | Active Disk | |
|---|---|---|---|---|---|---|
| | Files | Code | Files | Code | Files | Code |
| access | 72 | 26,385 | - | - | 1 | 838 |
| bootstrap | 2 | 1,259 | - | - | - | - |
| catalog | 43 | 13,584 | - | - | - | - |
| commands | 34 | 11,635 | - | - | - | - |
| executor | 49 | 17,401 | 9 | 938 | 4 | 3,574 |
| parser | 31 | 9,477 | - | - | - | - |
| lib | 35 | 7,794 | - | - | - | - |
| nodes | 24 | 13,092 | - | - | 6 | 4,130 |
| optimizer | 72 | 19,187 | - | - | - | - |
| port | 5 | 514 | - | - | - | - |
| regex | 12 | 4,665 | - | - | - | - |
| rewrite | 13 | 5,462 | - | - | - | - |
| storage | 50 | 17,088 | 1 | 273 | - | - |
| tcop | 11 | 4,054 | - | - | - | - |
| utils/adt | 40 | 31,526 | - | - | 2 | 315 |
| utils/fmgr | 4 | 2,417 | - | - | 1 | 281 |
| utils | 81 | 19,908 | - | - | 1 | 47 |
| Total | 578 | 205,448 | 10 | 1,211 | 15 | 9,185 |
| | | | | | New | 1,257 |

# Code Specialization

| query | type | computation (instr/byte) | throughput (MB/s) | memory (KB) | selectivity (factor) | instructions (KB) |
|---|---|---|---|---|---|---|
| Q1 | aggregation | 1.82 | 73.1 | 488 | 816 | 9.1/4.7 |
| Q13 | hash-join | 0.15 | 886.7 | 576 | 967,000 | 14.3/10.5 |

## Optimized Implementation

- **direct C code, single query only, raw binary files**
- **133 MHz Alpha 3000/400, Digital UNIX 3.2**

| operation | computation (cycles/byte) | throughput (MB/s) | selectivity (factor) |
|---|---|---|---|
| Scan | 28 | 17.8 | 4.00 |
| Qualification | 29 | 17.2 | 1.05 |
| Sort/Group | 71 | 7.0 | 1.00 |
| Sort/Aggregate | 196 | 2.5 | 3,770.00 |

## Database System

- **database manager database is PostgreSQL 6.4.2**
- **much higher cycles/byte than direct C implementation**
  - **parses general SQL statements**
  - **handles arbitrary tuple formats**

# History - SCAFS

## SCAFS (Son of Content-Addressable File Store)

- processing unit in a 3.5” form factor, fit into a drive shelf
- communication via SCSI commands

## Goals

- invisible to the application layer (i.e. hidden under SQL)
- established as an industry-standard for high volume market

## Benefits

- 40% to 3x throughput improvement in a mixed workload
- 20% to 20x improvement in response time
- 2x to 20x for a “pure” decision support workload
- up to 100x improvement in response time

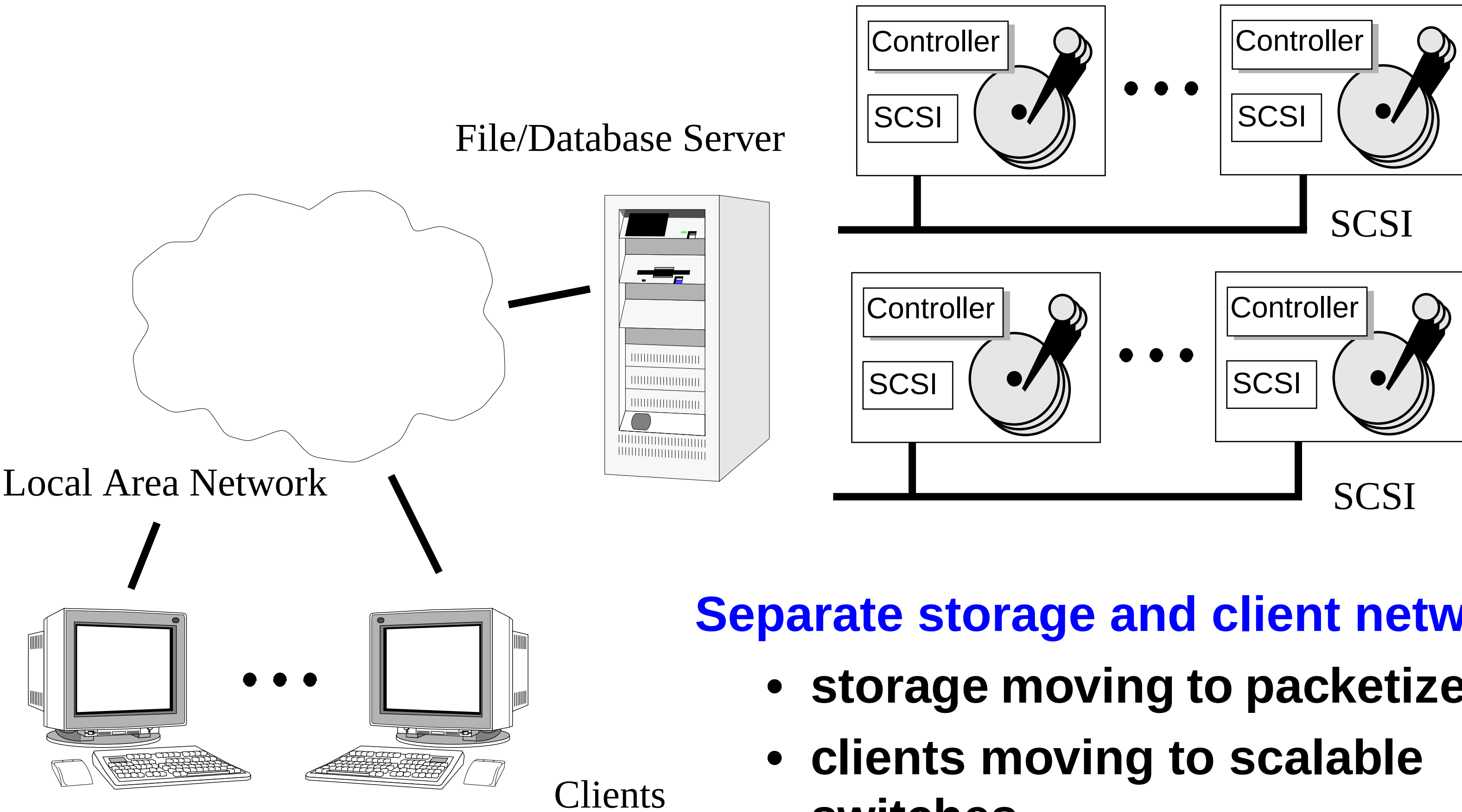
# Lessons from CAFS [Anderson98]

## Why did CAFS not become wildly popular?

- **“synchronization was a big problem”**
  ***Answer*** **- Yes. Major concern for OLTP, less for “mining”.**
- **“dynamic switching between applications is a problem”**
  ***Answer*** **- Yes. But operating systems know how to do this.**
- **“not the most economical way to add CPU power”**
  ***Answer*** **- but it *is* the best bandwidth/capacity/compute combo and you can still add CPU if that helps (and if you can keep it fed)**
- **“CPU is a more flexible resource”, disk processor wasted when not in use**
  ***Answer*** **- you’re already wasting it today, silicon is everywhere**
- **“memory size is actually a bigger problem”**
  ***Answer*** **- use adaptive algorithms, apps have “sweet spots”**
- **“needed higher volume, lower cost function”**
  ***Answer*** **- this is exactly what the drive vendors can provide no specialized, database-specific hardware necessary**
- **“could not get it to fit into the database world”**
  ***Answer*** **- proof of concept, community willing to listen**

# Yesterday's Server-Attached Disks

## Store-and-forward data copy through server machine



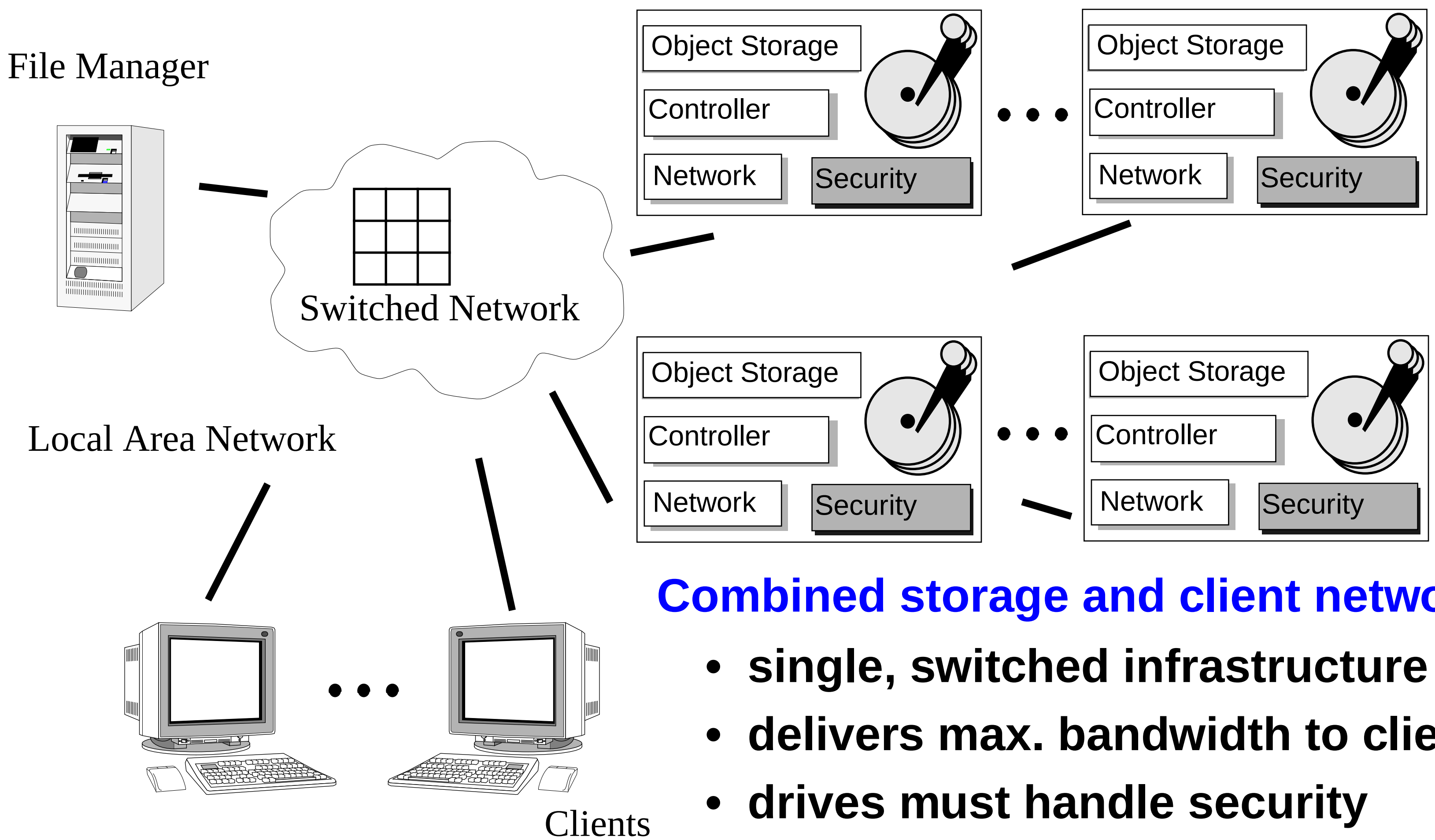

**Separate storage and client networks**

- **storage moving to packetized FC**
- **clients moving to scalable switches**

# Network-Attached Secure Disks

**Eliminate server bottleneck w/ network-attached**

- **server scaling [SIGMETRICS ‘97]**
- **object interface, filesystems [CMU-CS ‘98]**
- **cost-effective, high bandwidth [ASPLOS ‘98]**




**Combined storage and client networks**

- **single, switched infrastructure**
- **delivers max. bandwidth to clients**
- **drives must handle security**

# TPC-D Benchmark

## Consists of *high selectivity*, *ad-hoc* queries

| | entire query | | | scan only | |
|---|---|---|---|---|---|
| **query** | **input** (MB) | **result** (KB) | **selectivity** (factor) | **input** (MB) | **selectivity** (factor) |
| Q1 | 672 | 0.2 | 4.8 million | 672 | 3.3 |
| Q5 | 857 | 0.09 | 9.7 million | 672 | 3.5 |
| Q7 | 857 | 0.02 | 3.5 million | 672 | 4.0 |
| Q9 | 976 | 6.5 | 154,000 | 672 | 2.2 |
| Q11 | 117 | 0.3 | 453,000 | 115 | 7.2 |

Scale Factor = 1 GB

## Simple filtering on input

- **factors of 3x and more savings in load on interconnect**

## Entire queries (including aggregation and joins)

- **factors of 100,000 and higher savings**

# Implementation Issues

## Partitioning

- combining disk code with “traditional” code

## Mobility

- code must run on disks and/or host
- Java (!) (?)
  - + popular, tools (coming soon), strong typing
  - - somewhat different emphasis what to optimize for
- more “static” extensions

## Interfaces

- capability system of NASD as a base
- additional inquiry functions for scheduling
- additional power (via capabilities) for storage mgmt

# Value-Added Storage

## Variety of value-added storage devices

| System | Function | Cost | Premium | Other |
|---|---|---|---|---|
| Seagate Cheetah 18LP LVD | disk only | $900 | - | 18 GB, lvd, 10,000 rpm |
| Seagate Cheetah 18LP FC | disk only | $942 | 5% | FC |
| Dell 200S PowerVault | drive shelves & cabinet | $10,645 | 48% | 8 lvd disks |
| Dell 650F PowerVault | dual RAID controllers | $32,005 | 240% | 10 disks, full FC |
| Dell 720N PowerVault | CIFS, NFS, Filer | $52,495 | 248% | 16 disks, ether, 256/8 cache |
| EMC Symmetrix 3330-18 | RAID, management | $160,000 | 962% | 16 disks, 2 GB cache |

## Price premium

- **cabinet cost is significant**
- **network-attached storage is as costly as RAID**
- **“management” gets the biggest margin**

# Network “Appliances” Can Win Today



## *Dell PowerEdge & PowerVault System*

Dell PowerVault 650F $40,354 x 12 =484,248
512 MB cache, dual link controllers, additional 630F cabinet, 20 x 9 GB FC disks, software support, installation
Dell PowerEdge 6350 $11,512 x 12 = 138,144
500 MHz PIII, 512 MB RAM, 27 GB disk
3Com SuperStack II 3800 Switch 7,041
10/100 Ethernet, Layer 3, 24-port
Rack Space for all that 20,710

## *NASRaQ System*



Cobalt NASRaQ $1,500 x 240 =360,000
250 MHz RISC, 32 MB RAM, 2 x 10 GB disks
Extra Memory (to 128 MB each) $183 x 360= 65,880
3Com SuperStack II 3800 Switch $7,041 x 11= 77,451
240/24 = 10 + 1 to connect those 10
Dell PowerEdge 6350 Front-End 11,512
Rack Space (estimate 4x as much as the Dells) 82,840
Installation & Misc 50,000

## ***Comparison***

| | Dell | Cobalt |
|---|---|---|
| *Storage* | 2.1 TB | 4.7 TB |
| *Spindles* | 240 | 480 |
| *Compute* | 6 GHz | 60 GHz |
| *Memory* | 12.3 GB | 30.7 GB |
| *Power* | 23,122 W | 12,098 W |
| *Cost* | $650,143 | $647,683 |