Computer Organization and Structure

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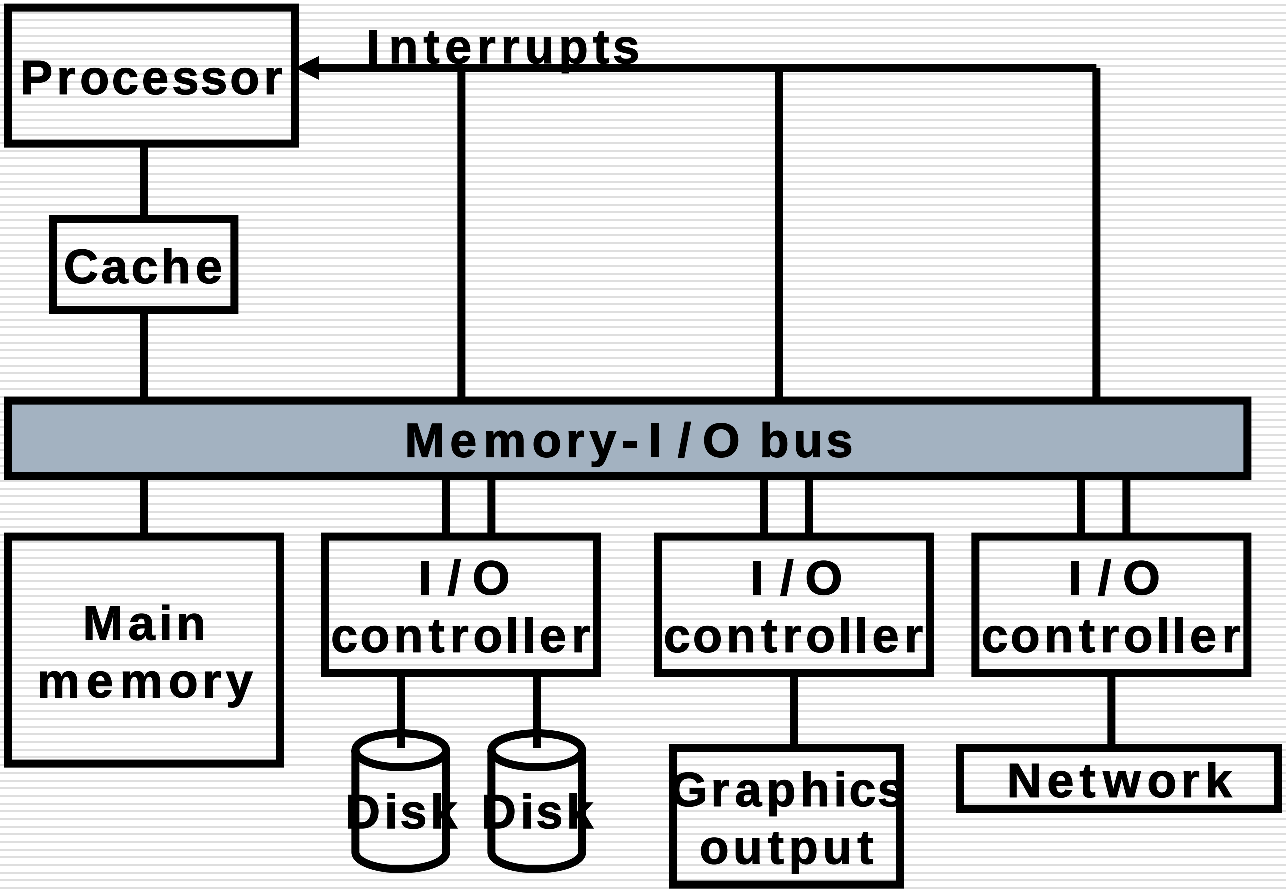
Storage and Other I/O Topics

- I/O Performance Measures
- Types and Characteristics of I/O Devices
- Buses
- Interfacing I/O Devices to the Memory, Processor, and OS
- Designing an I/O System

I/O Design

- I/O devices can be characterized by
  - Behavior: input, output, storage
  - Partner: human or machine
  - Data rate: bytes/sec, transfers/sec
- I/O bus connections

Typical Collection of I/O Devices



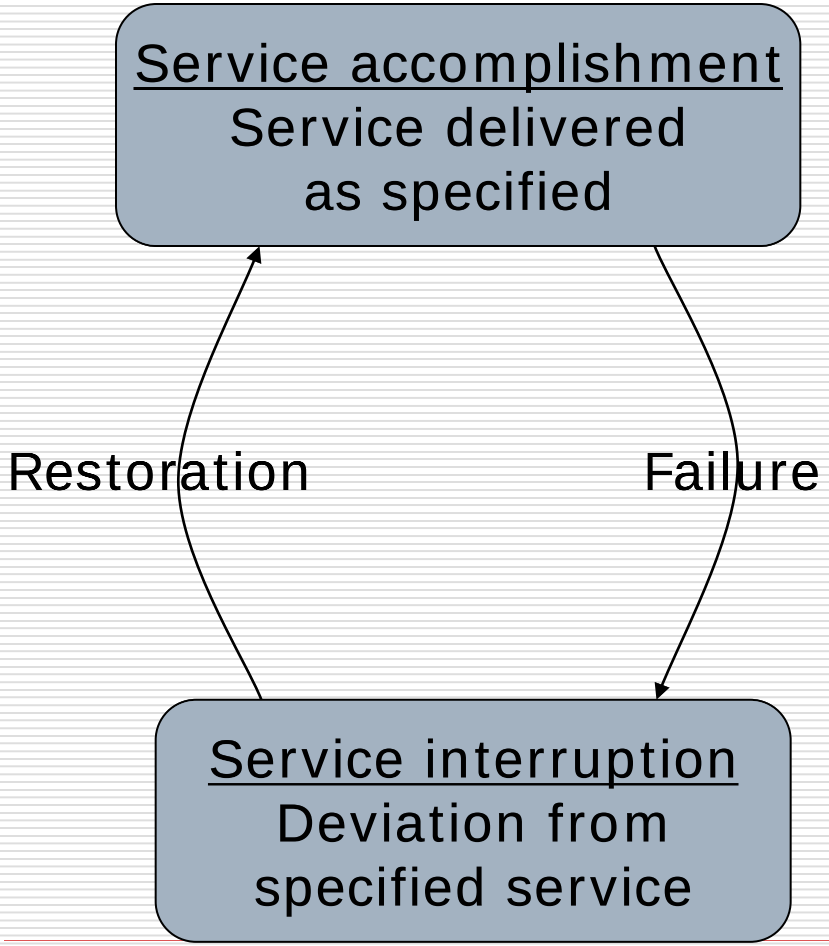
Types and Characteristics of I/O Devices

device	behavior	partner	data rate (MB/sec.)
Keyboard	input	human	0.0001
Mouse	input	human	0.0038
Voice Input	input	human	0.2640
Sound Input	input	machine	3.0000
Scanner	input	human	3.2000
Voice Output	output	human	0.2640
Sound Output	output	human	8.0000
Laser Printer	output	human	3.2000
Graphics Display	output	human	800.0000-8000.0000
Cable Modem	input or output	machine	0.1280-6.0000
Network / LAN	input or output	machine	100.0000-10000.0000
Network / wireless LAN	input or output	machine	11.0000-54.0000
Optical Disk	storage	machine	80.0000-220.0000
Magnetic Tape	storage	machine	5.0000-120.0000
Flash Memory	storage	machine	32.0000-200.0000
Magnetic Disk	storage	machine	800.0000-3000.0000

I/O System Characteristics

- Dependability is important
  - Particularly for storage devices
- Performance measures
  - Latency (response time)
  - Throughput (bandwidth)
  - Desktops & embedded systems
    - Mainly interested in response time & diversity of devices
  - Servers
    - Mainly interested in throughput & expandability of devices

Dependability



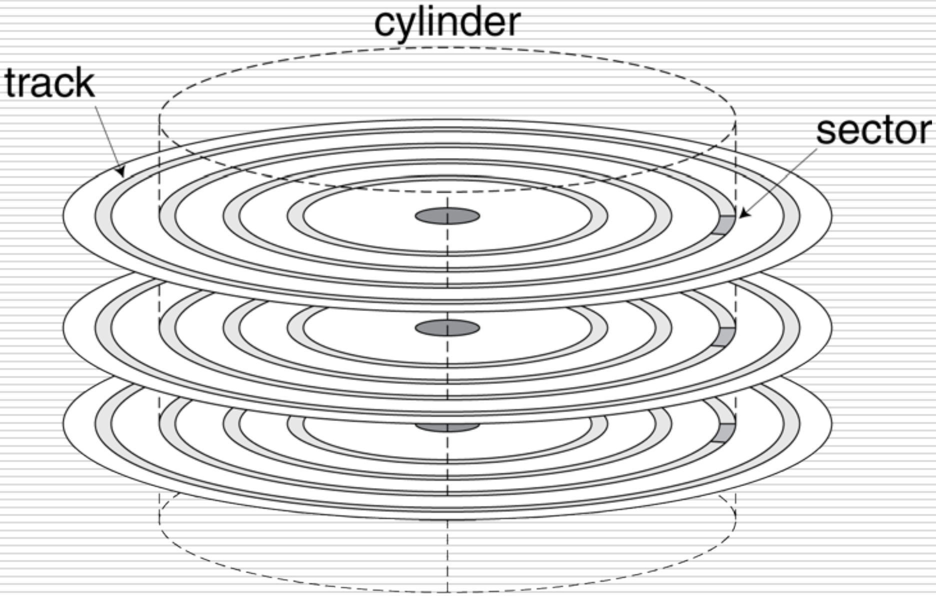
- Fault: failure of a component
  - May or may not lead to system failure

Dependability Measures

- Reliability: mean time to failure (MTTF)
- Service interruption: mean time to repair (MTTR)
- Mean time between failures
  - MTBF = MTTF + MTTR
- Availability = MTTF / (MTTF + MTTR)
- Improving Availability
  - Increase MTTF: fault avoidance, fault tolerance, fault forecasting
  - Reduce MTTR: improved tools and processes for diagnosis and repair

Disk Storage

- Nonvolatile, rotating magnetic storage



Disk Sectors and Access

- Each sector records
  - Sector ID
  - Data (512 bytes, 4096 bytes proposed)
  - Error correcting code (ECC)
    - Used to hide defects and recording errors
  - Synchronization fields and gaps
- Access to a sector involves
  - Queuing delay if other accesses are pending
  - Seek: move the heads
  - Rotational latency
  - Data transfer
  - Controller overhead

Disk Access Example

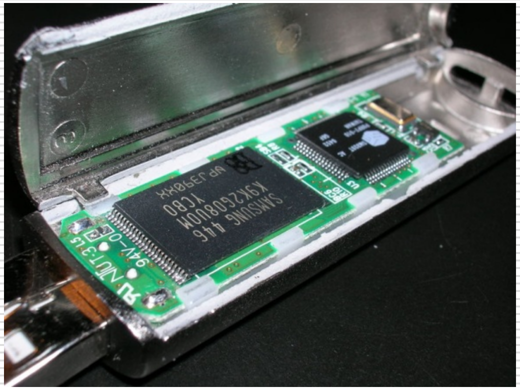
- Given
  - 512B sector, 15,000rpm, 4ms average seek time, 100MB/s transfer rate, 0.2ms controller overhead, idle disk
- Average read time
  - 4ms seek time
    + ½ / (15,000/60) = 2ms rotational latency
    + 512 / 100MB/s = 0.005ms transfer time
    + 0.2ms controller delay
    = 6.2ms
- If actual average seek time is 1ms
  - Average read time = 3.2ms

Disk Performance Issues

- Manufacturers quote average seek time
  - Based on all possible seeks
  - Locality and OS scheduling lead to smaller actual average seek times
- Smart disk controller allocate physical sectors on disk
  - Present logical sector interface to host
  - SCSI, ATA, SATA
- Disk drives include caches
  - Prefetch sectors in anticipation of access
  - Avoid seek and rotational delay

Flash Storage

- Non-volatile semiconductor storage
  - 100× – 1000× faster than disk
  - Smaller, lower power, more robust
  - But more $/GB (between disk and DRAM)



Flash Types

- NOR flash: bit cell like a NOR gate
  - Random read/write access
  - Used for instruction memory in embedded systems
- NAND flash: bit cell like a NAND gate
  - Denser (bits/area), but block-at-a-time access
  - Cheaper per GB
  - Used for USB keys, media storage, ...
- Flash bits wears out after 1000's of accesses
  - Not suitable for direct RAM or disk replacement
  - Wear levelling: remap data to less used blocks

Interconnecting Components

- Need interconnections between
  - CPU, memory, I/O controllers
- Bus: shared communication channel
  - Parallel set of wires for data and synchronization of data transfer
  - Can become a bottleneck
- Performance limited by physical factors
  - Wire length, number of connections
- More recent alternative: high-speed serial connections with switches
  - Like networks

Bus Types

- Processor-Memory buses
  - Short, high speed
  - Design is matched to memory organization
- I/O buses
  - Longer, allowing multiple connections
  - Specified by standards for interoperability
  - Connect to processor-memory bus through a bridge

Bus Signals and Synchronization

- Data lines
  - Carry address and data
  - Multiplexed or separate
- Control lines
  - Indicate data type, synchronize transactions
- Synchronous
  - Uses a bus clock
- Asynchronous
  - Uses request/acknowledge control lines for handshaking

I/O Bus Examples

	Firewire	USB 2.0	PCI Express	Serial ATA	Serial Attached SCSI
Intended use	External	External	Internal	Internal	External
Devices per channel	63	127	1	1	4
Data width	4	2	2/lane	4	4
Peak bandwidth	50MB/s or 100MB/s	0.2MB/s, 1.5MB/s, or 60MB/s	250MB/s/lane 1×, 2×, 4×, 8×, 16×, 32×	300MB/s	300MB/s
Hot pluggable	Yes	Yes	Depends	Yes	Yes
Max length	4.5m	5m	0.5m	1m	8m
Standard	IEEE 1394	USB Implementers Forum	PCI-SIG	SATA-IO	INCITS TC T10

I/O Management

- I/O is mediated by the OS
  - Multiple programs share I/O resources
    - Need protection and scheduling
  - I/O causes asynchronous interrupts
    - Same mechanism as exceptions
  - I/O programming is fiddly
    - OS provides abstractions to programs

I/O Commands

- I/O devices are managed by I/O controller hardware
  - Transfers data to/from device
  - Synchronizes operations with software
- Command registers
  - Cause device to do something
- Status registers
  - Indicate what the device is doing and occurrence of errors
- Data registers
  - Write: transfer data to a device
  - Read: transfer data from a device

I/O Register Mapping

- Memory mapped I/O
  - Registers are addressed in same space as memory
  - Address decoder distinguishes between them
  - OS uses address translation mechanism to make them only accessible to kernel
- I/O instructions
  - Separate instructions to access I/O registers
  - Can only be executed in kernel mode
  - Example: x86

Polling

- Periodically check I/O status register
  - If device ready, do operation
  - If error, take action
- Common in small or low-performance real-time embedded systems
  - Predictable timing
  - Low hardware cost
- In other systems, wastes CPU time

Interrupts

- When a device is ready or error occurs
  - Controller interrupts CPU
- Interrupt is like an exception
  - But not synchronized to instruction execution
  - Can invoke handler between instructions
  - Cause information often identifies the interrupting device
- Priority interrupts
  - Devices needing more urgent attention get higher priority
  - Can interrupt handler for a lower priority interrupt

I/O Data Transfer

- Polling and interrupt-driven I/O
  - CPU transfers data between memory and I/O data registers
  - Time consuming for high-speed devices
- Direct memory access (DMA)
  - OS provides starting address in memory
  - I/O controller transfers to/from memory autonomously
  - Controller interrupts on completion or error

DMA/Cache Interaction

- If DMA writes to a memory block that is cached
  - Cached copy becomes stale
- If write-back cache has dirty block, and DMA reads memory block
  - Reads stale data
- Need to ensure cache coherence
  - Flush blocks from cache if they will be used for DMA
  - Or use non-cacheable memory locations for I/O

DMA/VM Interaction

- OS uses virtual addresses for memory
  - DMA blocks may not be contiguous in physical memory
- Should DMA use virtual addresses?
  - Would require controller to do translation
- If DMA uses physical addresses
  - May need to break transfers into page-sized chunks
  - Or chain multiple transfers
  - Or allocate contiguous physical pages for DMA

Measuring I/O Performance

- I/O performance depends on
  - Hardware: CPU, memory, controllers, buses
  - Software: operating system, database management system, application
  - Workload: request rates and patterns
- I/O system design can trade-off between response time and throughput
  - Measurements of throughput often done with constrained response-time

I/O vs. CPU Performance

- Amdahl's Law
  - Don't neglect I/O performance as parallelism increases compute performance
- Example
  - Benchmark takes 90s CPU time, 10s I/O time
  - Double the number of CPUs/2 years
    - I/O unchanged

Year	CPU time	I/O time	Elapsed time	% I/O time
now	90s	10s	100s	10%
+2	45s	10s	55s	18%
+4	23s	10s	33s	31%
+6	11s	10s	21s	47%

RAID

- Redundant Array of Inexpensive (Independent) Disks
  - Use multiple smaller disks (c.f. one large disk)
  - Parallelism improves performance
  - Plus extra disk(s) for redundant data storage
- Provides fault tolerant storage system
  - Especially if failed disks can be "hot swapped"
- RAID 0
  - No redundancy ("AID"?)
    - Just stripe data over multiple disks
  - But it does improve performance

RAID 1 & 2

- RAID 1: Mirroring
  - N + N disks, replicate data
    - Write data to both data disk and mirror disk
    - On disk failure, read from mirror
- RAID 2: Error correcting code (ECC)
  - N + E disks (e.g., 10 + 4)
  - Split data at bit level across N disks
  - Generate E-bit ECC
  - Too complex, not used in practice

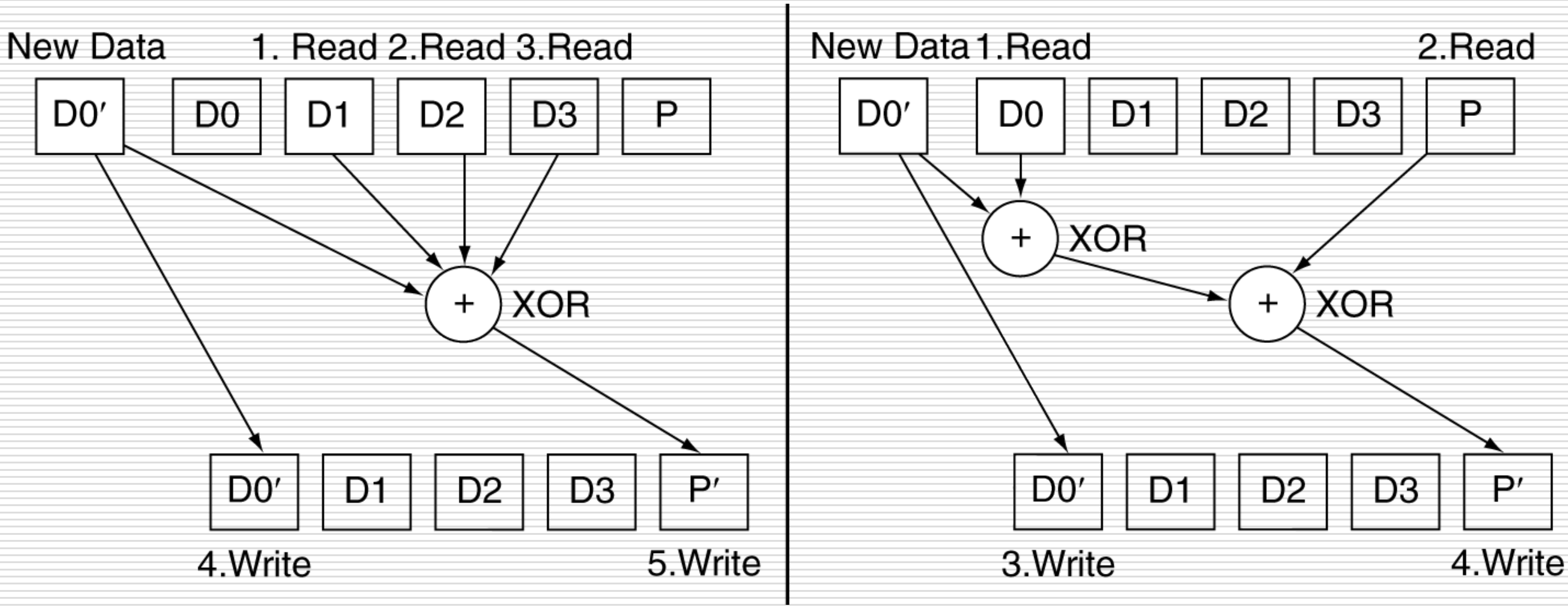
RAID 3: Bit-Interleaved Parity

- N + 1 disks
  - Data striped across N disks at byte level
  - Redundant disk stores parity
  - Read access
    - Read all disks
  - Write access
    - Generate new parity and update all disks
  - On failure
    - Use parity to reconstruct missing data
- Not widely used

RAID 4: Block-Interleaved Parity

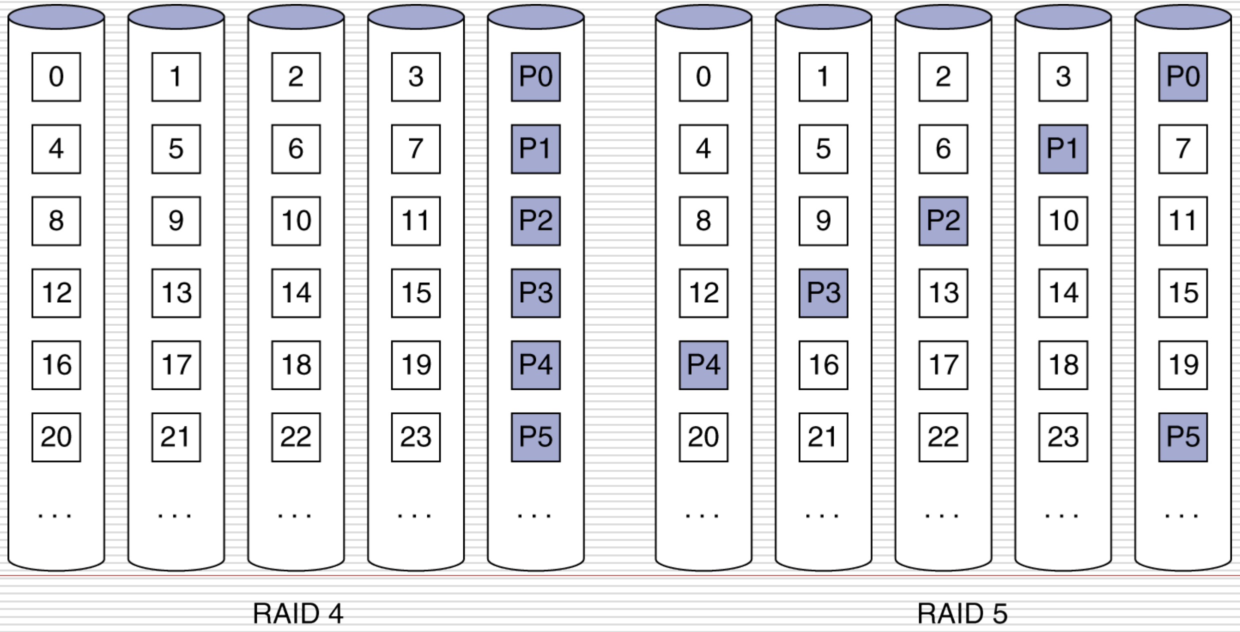
- N + 1 disks
  - Data striped across N disks at block level
  - Redundant disk stores parity for a group of blocks
  - Read access
    - Read only the disk holding the required block
  - Write access
    - Just read disk containing modified block, and parity disk
    - Calculate new parity, update data disk and parity disk
  - On failure
    - Use parity to reconstruct missing data
- Not widely used

RAID 3 vs RAID 4



RAID 5: Distributed Parity

- N + 1 disks
  - Like RAID 4, but parity blocks distributed across disks
    - Avoids parity disk being a bottleneck
- Widely used



RAID 6: P + Q Redundancy

- N + 2 disks
  - Like RAID 5, but two lots of parity
  - Greater fault tolerance through more redundancy
- Multiple RAID
  - More advanced systems give similar fault tolerance with better performance

I/O System Design

- Satisfying latency requirements
  - For time-critical operations
  - If system is unloaded
    - Add up latency of components
- Maximizing throughput
  - Find “weakest link” (lowest-bandwidth component)
  - Configure to operate at its maximum bandwidth
  - Balance remaining components in the system
- If system is loaded, simple analysis is insufficient
  - Need to use queuing models or simulation

Server Computers

- Applications are increasingly run on servers
  - Web search, office apps, virtual worlds, …
- Requires large data center servers
  - Multiple processors, networks connections, massive storage
  - Space and power constraints
- Server equipment built for 19” racks
  - Multiples of 1.75” (1U) high

Rack-Mounted Servers

Sun Fire x4150 1U server