CO 06 IO

1 Introduction

- Three characters of I/O
  - Behavior: input, output, storage
  - Partner: human/machine
  - Data rate: the **peak** rate at which data are transferred
- I/O 性能评价取决于应用场景
  - Throughput 吞吐量 (e.g. data center)
    - 数据传输速率
    - I/O 操作处理速率
  - Response time 响应时间 (e.g. PC)
  - both (e.g. booking systems)
- & I/O 设备的差异很大

1.1 Amdahl's Law

Example: 100 processors, 90× speedup?

- $T_{new} = T_{parallelizable}/100 + T_{sequential}$
- $\text{Speedup} = \dfrac{1}{(1 - F_{parallelizable}) + F_{parallelizable}/100} = 90$
- Solving: $F_{parallelizable} = 0.999$

> I/O 相比于 CPU 性能，更可能是瓶颈

2 Disks

- SSD
- HDD

2.1 Access Time

- Seek time: 磁头寻道时间，存在 min/maximum seek time
- Rotational latency: $0.5 \text{ rotation}/RPS$
- Transfer time: 读取和传输一个 sector 的时间
- Disk controller: 控制器延迟

$$\text{Access time} = \text{Seek time} + \text{Rotational Latency} + \text{Transfer time} + \text{Controller time}$$

2.2 Dependability, Reliability, Availability

- Dependability: reliability + availability
- Availability
  - $MTTF$ (mean time to failure) 发生错误的频率
  - $MTTR$ (mean time to repair) 修复时间
  - $MTBF$ (mean time between Failures) $= MTTF + MTTR$
  - $Availability = \frac{MTTF}{MTTF+MTTR} = \frac{MTTF}{MTBF}$

2.3 Array Reliability

- $\text{Reliability of } N \text{ disks} = \text{Reliability of 1 Disk}/N$
- $\text{AFR (annual failure rate)} = \text{percentage of devices to fail per year}$

- $= 8760/\text{MTTF of 1 device}$
- *nines of availability*

> **Three Ways to Improve MTTF**
>
> - Fault avoidance
> - Fault tolerance
> - Fault forecasting

2.4 RAID (Redundant Arrays of Inexpensive Disks)

- 提升 data availability
- 允许磁盘出错
- 数据冗余存储
  - capacity penalty
  - bandwidth penalty

RAID level		Minimum number of Disk faults survived	Example Data disks	Corre-sponding Check disks	Corporations producing RAID products at this level
0	Non-redundant striped	0	8	0	Widely used
1	Mirrored	1	8	8	EMC, Compaq (Tandem), IBM
2	Memory-style ECC	1	8	4	
3	Bit-interleaved parity	1	8	1	Storage Concepts
4	Block-interleaved parity	1	8	1	Network Appliance
5	Block-interleaved distributed parity	1	8	1	Widely used
6	P+Q redundancy	2	8	2	

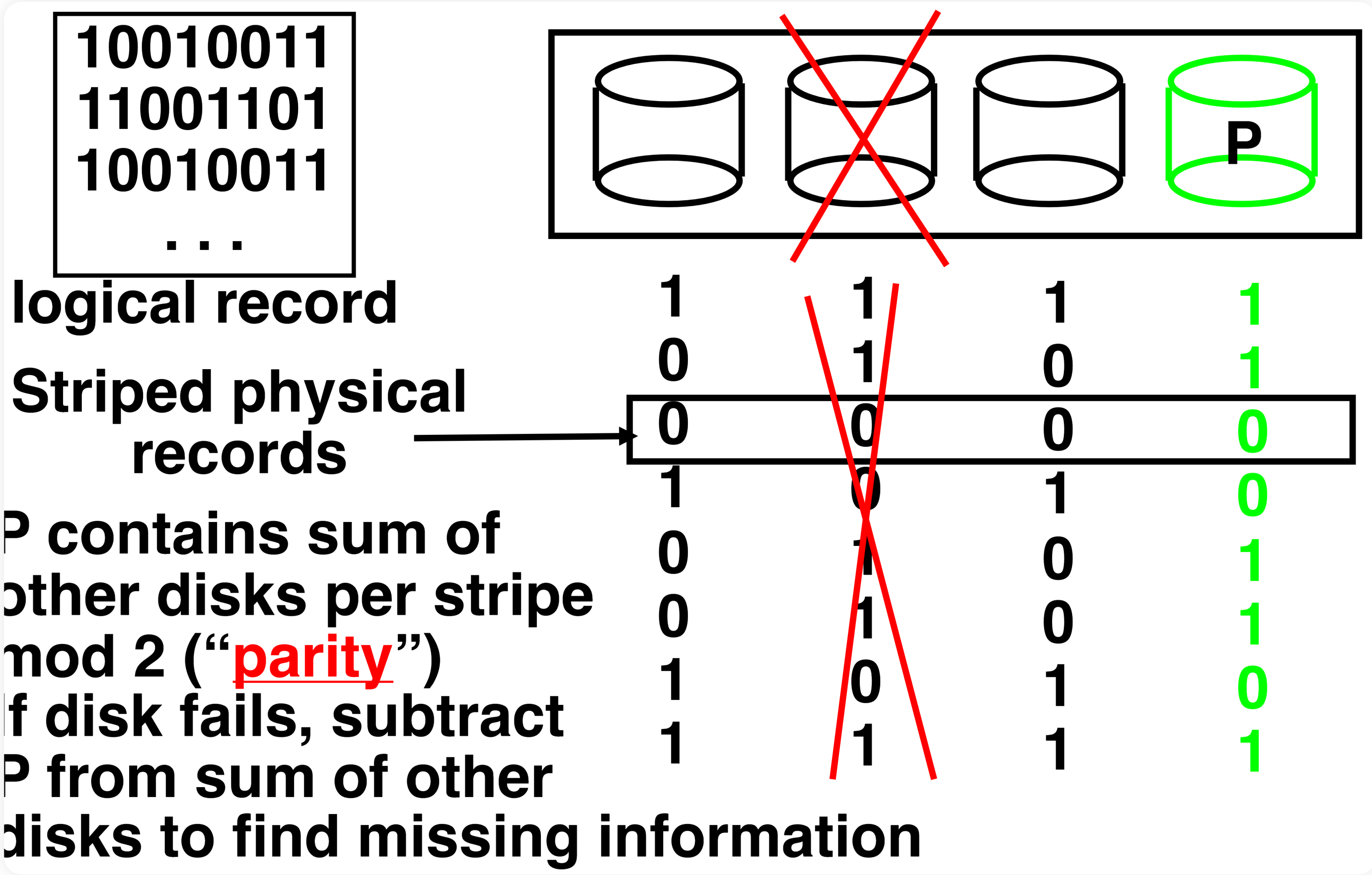
2.4.1 RAID 0: No Redundancy

- 数据可以跨磁盘存储，但是没有冗余
- 分布式访问，能够提升 performance

2.4.2 RAID 1: Mirroring/Shadowing

- 写开销增加
- 读性能能够优化，e.g. 从闲置磁盘读取
- 效率低，需要 100% 冗余

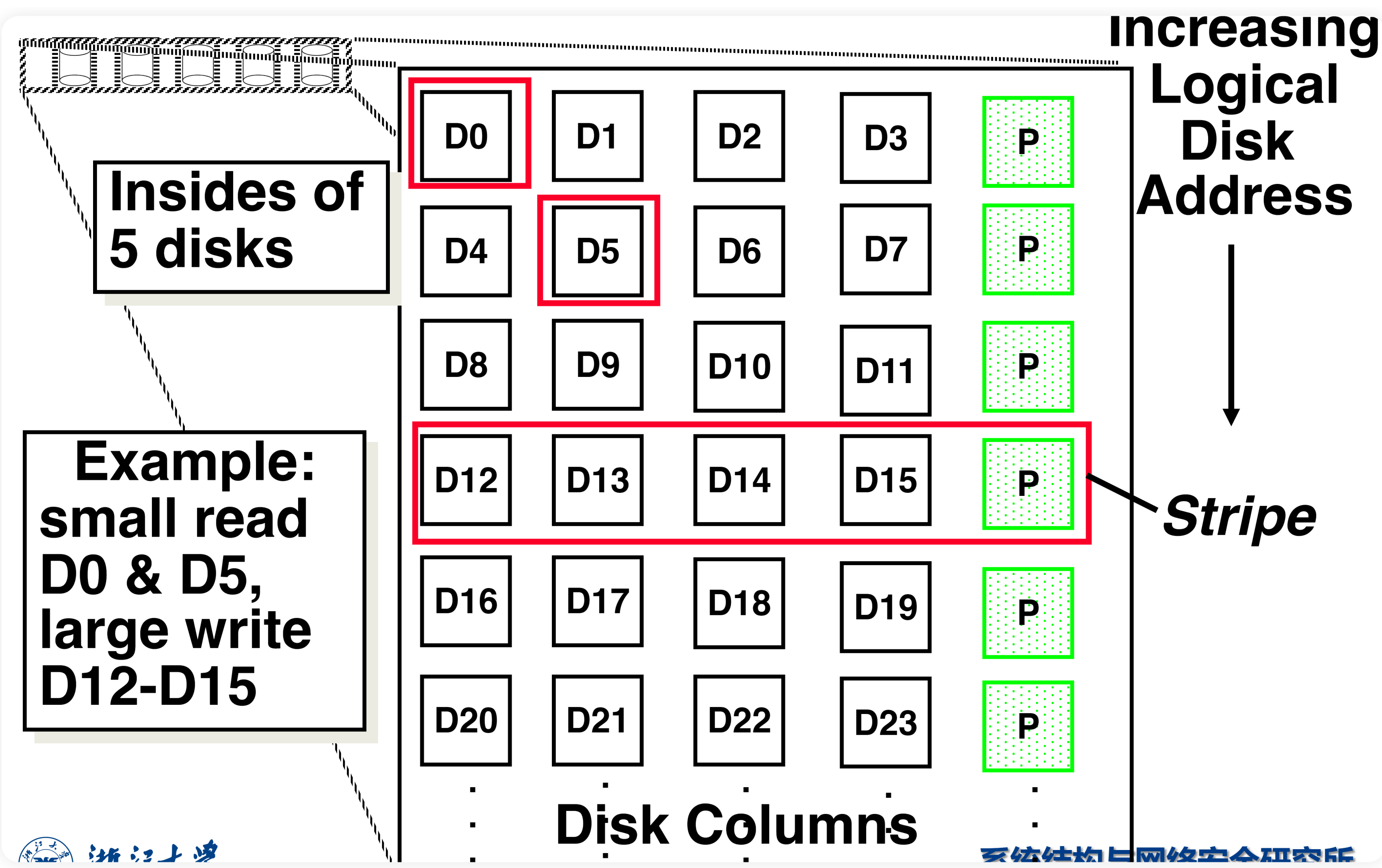
2.4.3 RAID 3: Bit-Interleaved Parity Disk



- 校验盘存储奇偶校验位
- 假设知道坏的盘，能通过其他盘恢复数据
- $ 能够实现热更换
- ！如果出现错误，读取开销会很高 *需要读取所有其他磁盘*

2.4.4 RAID 4: Block-Interleaved Parity

> 沿用 RAID 3 思想，但是按照 block 打包
> high I/O rate parity

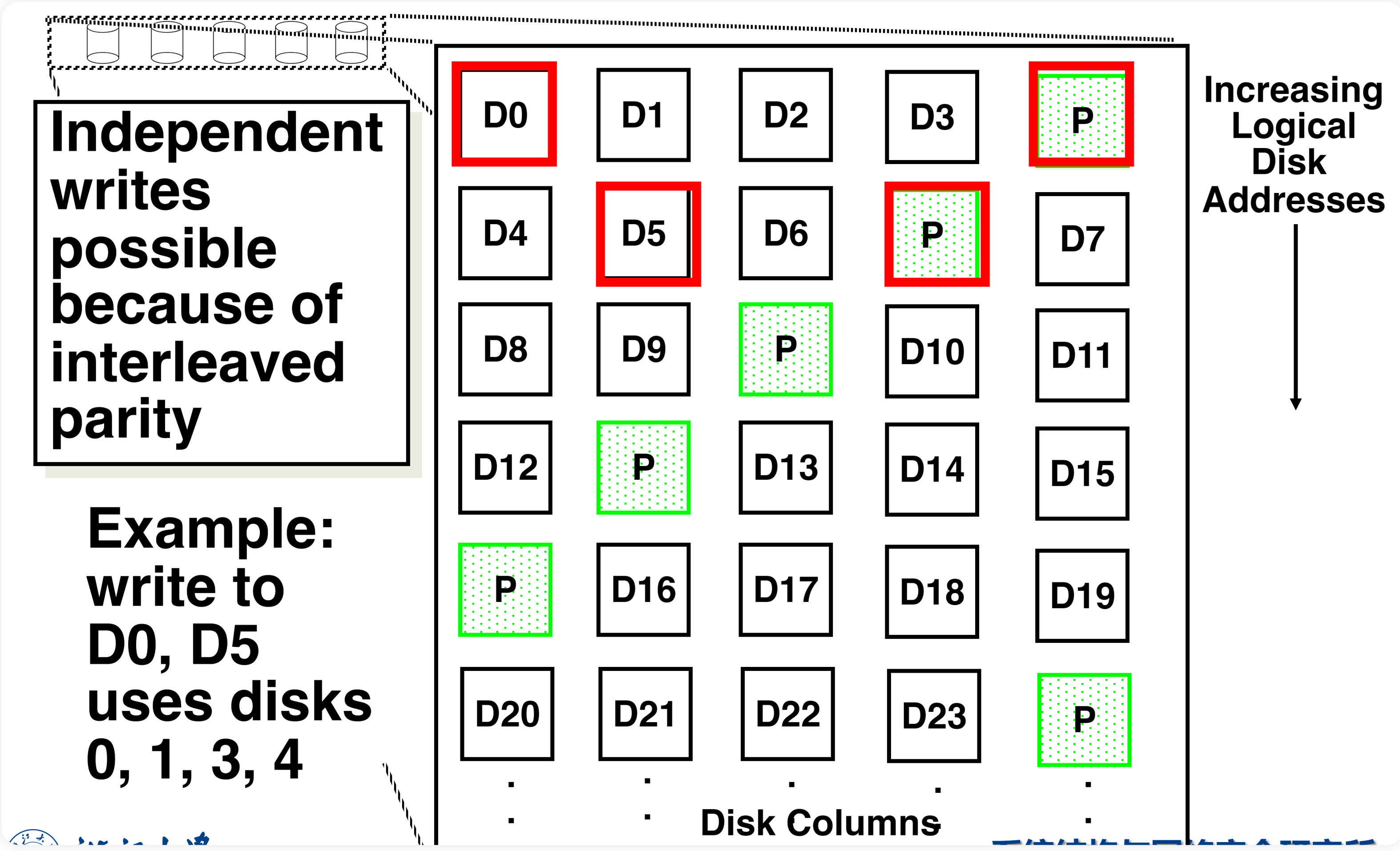


- ！Problem: Small Writes
  - 如果修改 D0，仍然需要重新读取所有盘来计算校验位
  - Algorithm: $P' = (D_0' \text{ XOR } D_0) \text{ XOR } P$
  - ！仍然存在问题，总是需要修改校验盘的数据

> 为什么 RAID 4 比 RAID 3 更好
>
> - RAID 3 中，数据是按照 0 1 2 0 1 2 的顺序存储的，称为 **striped physical records**
> - 如果访问较大的数据，需要同时读取所有数据盘

- 如果按照 block 分块，则更大概率只需要访问一个盘

2.4.5 RAID 5: High I/O Rate Interleaved Parity

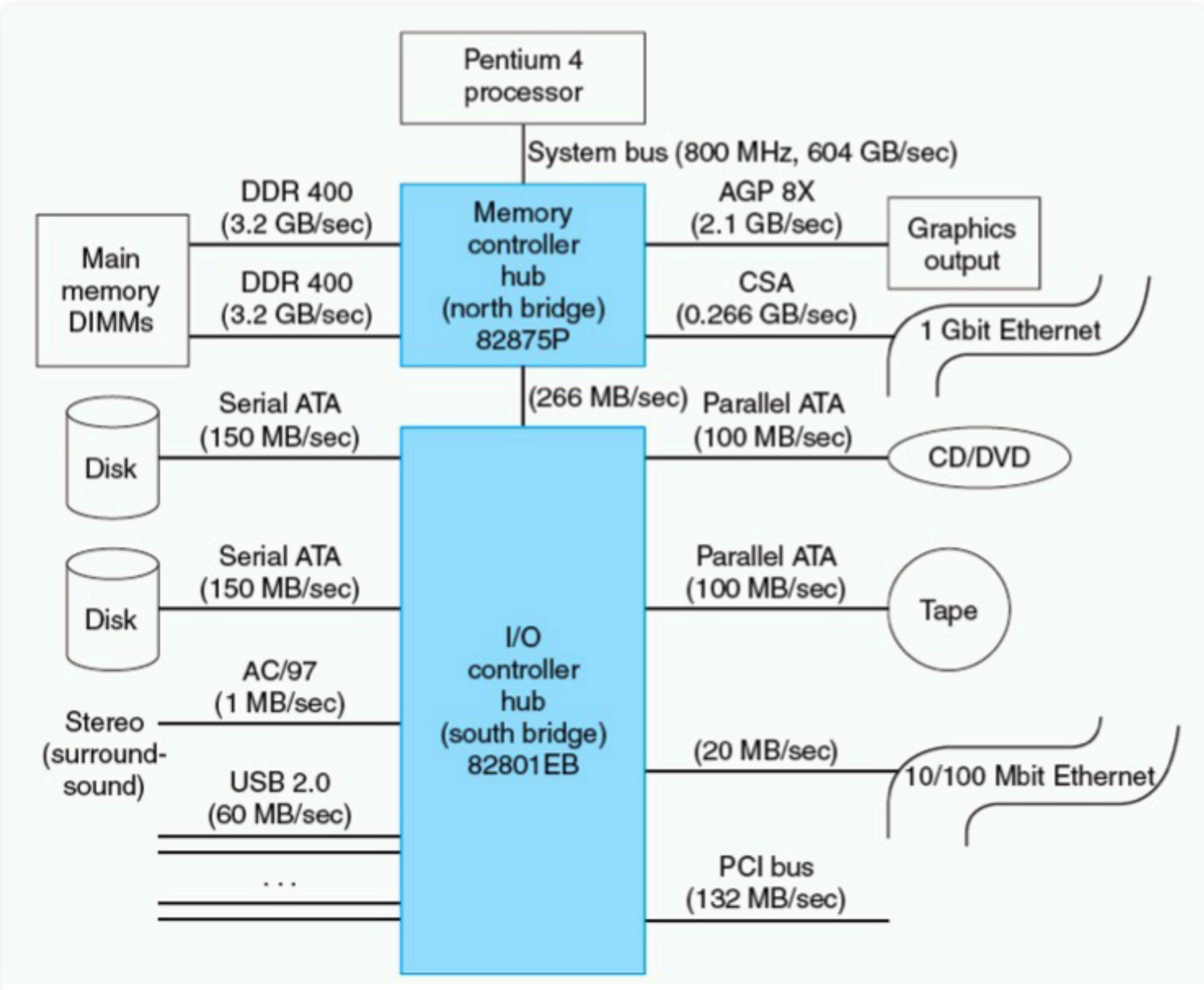


- $ 写时分散更新 parity

2.4.6 RAID 6: P+Q Redundancy

> 允许两个磁盘同时出错

3 Buses and Other Connections

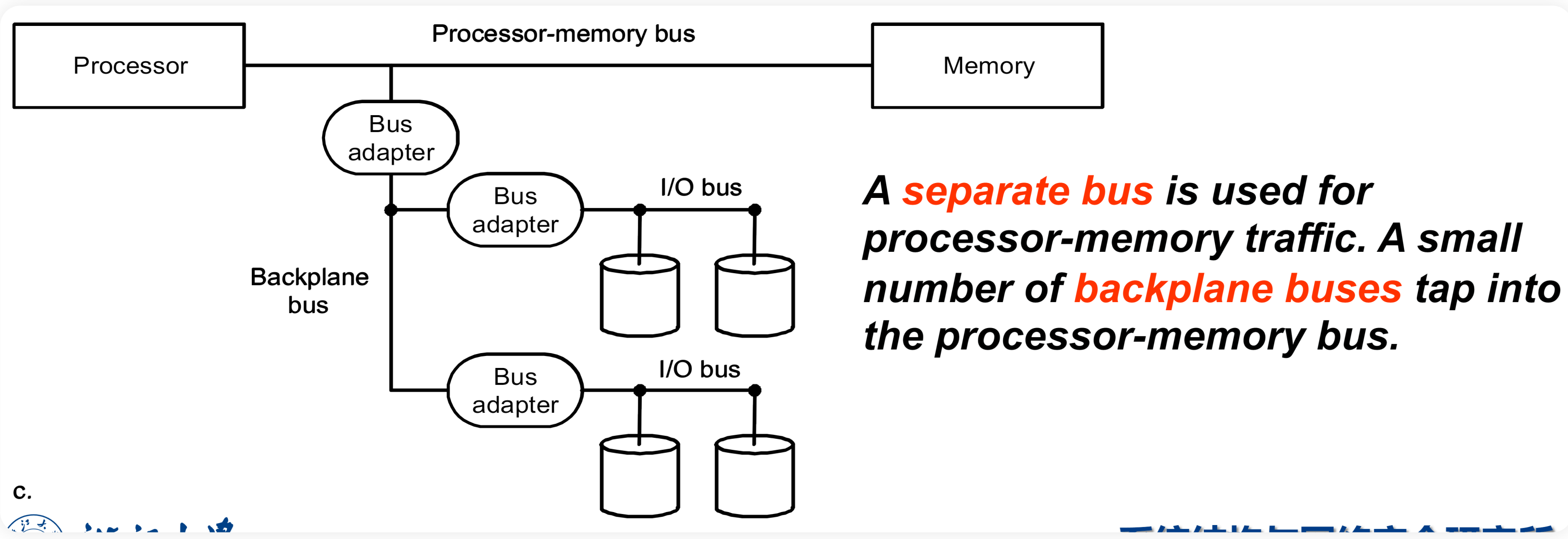


- North Bridge (Memory Controller) 速度更快

- Memory
  - Graphic
- South Bridge (I/O Controller)
  - Disk
  - USB

3.1 Buses Basics

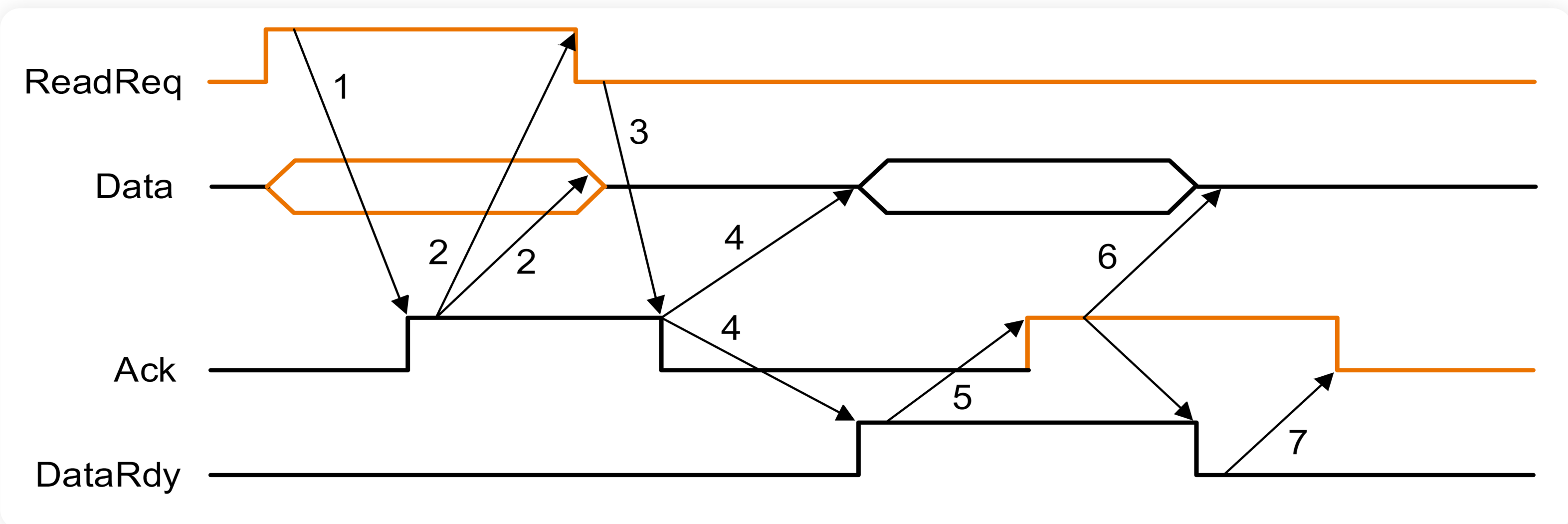
- Shared communication link
- 2 types of lines
  - Control lines
  - Data lines
- 2 operations
  - input: 数据从 device 到 memory
  - output: 数据从 memory 到 device
- 3 types of buses
  - Processor-memory
  - Backplane
  - I/O



3.2 Synchronous vs. Asynchronous

- sync
  - ! 所有设备需要工作在同一频率
  - ! 总线不能太长，否则 clock skew
  - $ fast and small
- async
  - hand shaking

3.2.1 Handshaking Protocol



> 橙色信号是 I/O device 发出的，黑色信号是内存发出的
> 除了 4，其他箭头都表示 bus 延迟

1. memory 得到 `ReadReq` 信号，读入 bus 上的 addr，然后升起 `Ack` 信号
2. I/O device 得到 `Ack` 信号，降低 `ReadReq` 信号
3. memory 得到 `ReadReq` 下降，降低 `Ack` ，释放总线

4. memory 准备好 data 之后，升起 `DataRdy`，将 data 放到 bus 上
5. I/O device 得到 `DataRdy` 信号，读入 data，升起 `Ack`
6. memory 得到 `Ack`，降低 `DataRdy`
7. I/O device 得到 `DataRdy` 下降，降低 `Ack`，释放总线

3.2.2 Arbitration 仲裁

> 设置 bus master (CPU is always a bus master)，管理请求

1. I/O device 向 CPU 发出请求
2. CPU 响应并给 memory 访存的 bus control signal
3. I/O device 开始访存，CPU 进行监控

仲裁的两个考虑因素

- bus priority 设备优先级
- fairness 总线长度问题

3.2.3 计算题

Assume: The synchronous bus has a clock cycle time of 50 ns, and each bus transmission takes 1 clock cycle .
The asynchronous bus requires 40 ns per handshake.
The data portion of both buses is 32 bits wide.
Question: Find the bandwidth for each bus when reading one word from a 200-ns memory.

- sync
  - 传输 addr 50ns
  - 访存 200ns
  - 传输 data 50ns
  - 300ns, $\text{bandwidth} = 4\text{B}/300\text{ns} = 13.3\text{MB/s}$
- async
  - step 1: 40ns
  - step 2, 3, 4: $\max(2 \times 40\text{ns}, 200\text{ns}) = 200\text{ns}$
  - step 5, 6, 7: $3 \times 40\text{ns} = 120\text{ns}$
  - 360ns, $\text{bandwidth} = 4\text{B}/360\text{ns} = 11.1\text{MB/s}$

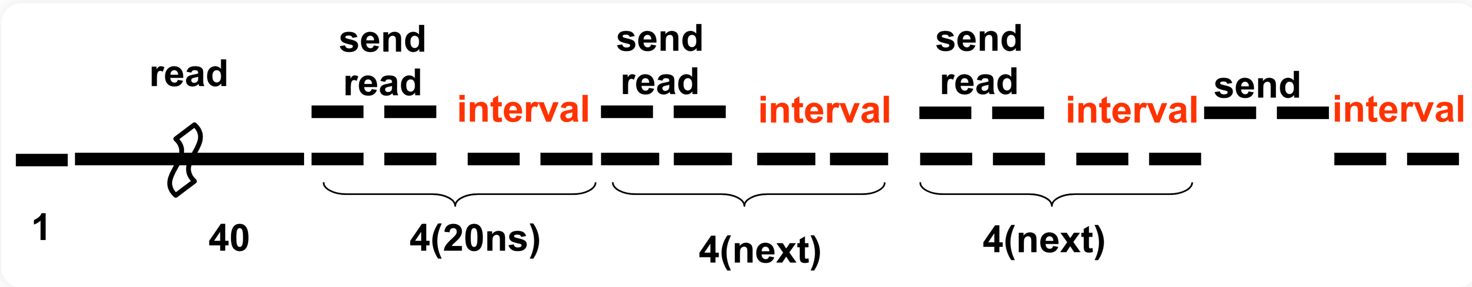
3.2.4 Increase bandwidth

Suppose **we have a system with the following characteristic**:

1. A memory and bus system supporting block access of 4 to 16 32-bit words
2. A 64-bit synchronous bus clocked at 200 MHz, with each 64-bit transfer taking 1 clock cycle, and 1 clock cycle required to send an address to memory.
3. Two clock cycles needed between each bus operation.
4. A memory access time for the first four words of 200ns; each additional set of four words can be read in 20 ns. Assume that a bus transfer of the most recently read data and a read of the next four words can be overlapped.

Find the sustained bandwidth and the latency for a **read of 256 words** for **transfers that use 4-word blocks** and for **transfers that use 16-word blocks**. Also compute effective number of bus transactions per second for each case.

- 4 word
  - send addr to memory: 1 cycle
  - read memory, 200ns, 40 cycles
  - send data: 2 cycles，因为需要传输 2 次，一次 64 bit
  - between operation: 2 cycles
  - total: $45\text{cycles} \times 64\text{blocks} = 2880\text{cycles}$
- 16 word
  - 单次 bus operation



  - 内存访存一次得到 4 个 word
  - 总线宽度是 64 bit，同时传输 2 word，一次访存需要两个 cycle 来传输
  - 一个 operation 读取 16 个 32 word，需要读取 4 次数据，其中第一次需要 40 cycle，其他只用 4 cycle，每次取数据的间隙就能够完成上一轮 4 个 word 的传输，所以存在 interval
    - 前三个 interval 是访存时间决定的
    - 最后一个 interval 是因为总线存在 2 个周期的延迟
  - 256 word 一共需要 16 次 operation: $57\text{cycles} \times 16\text{blocks} = 912\text{cycles}$

> **Tip**
>
> 使用更大的 block 能够提升总线带宽

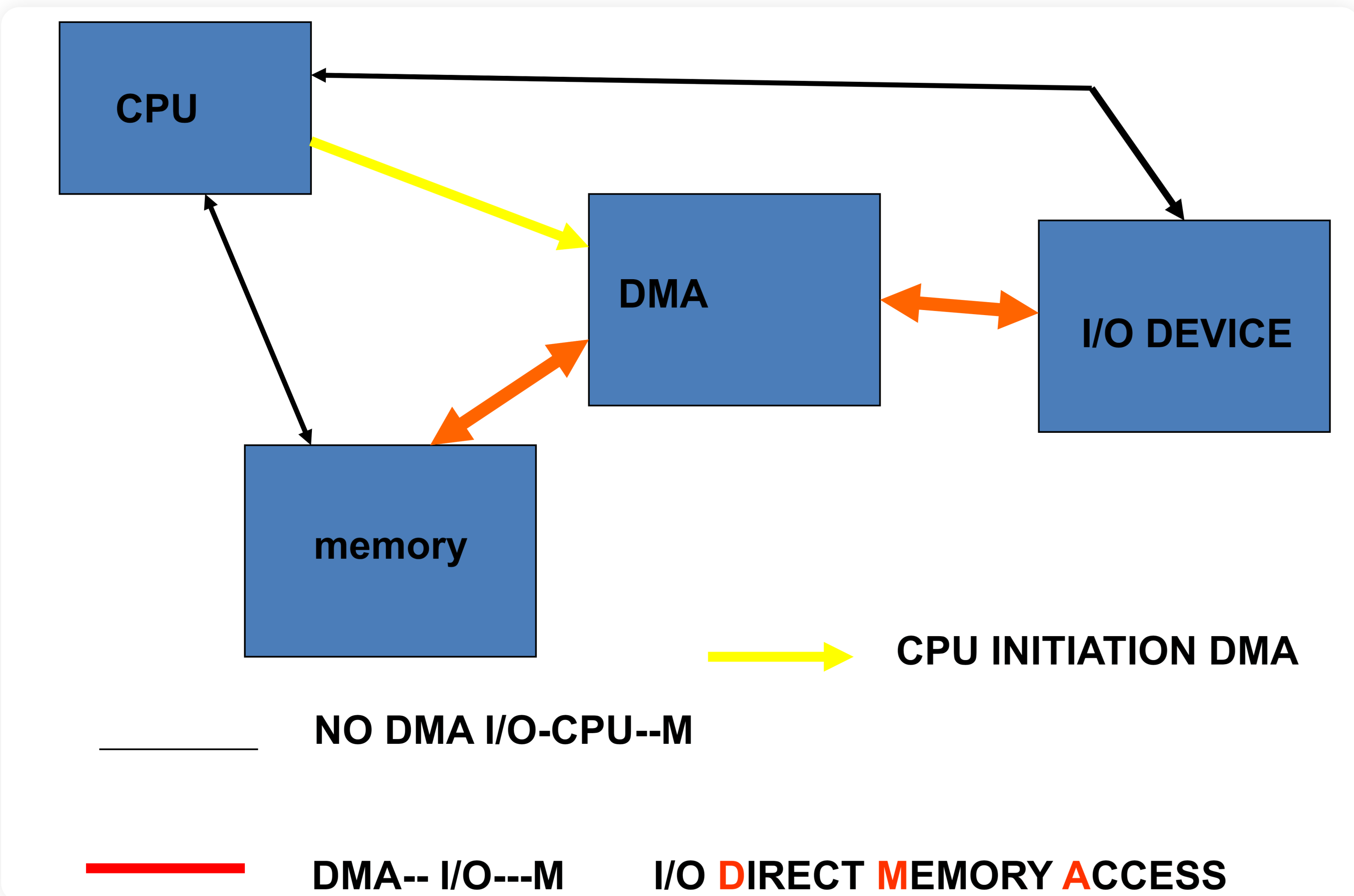
4 Interfacing I/O Devices

4.1 I/O 指令的种类

- memory-mapped I/O: 将设备映射到内存地址，使用访存指令就可以进行 I/O 设备控制
- special I/O inst: `in a1, port`
- command port, data port: status reg, data reg...

4.2 I/O to processor

- polling: 每隔多少周期检查一次 I/O
- interrupt: I/O 中断
  - DMA (direct memory access): device controller 在 I/O 和 memory 中传输数据



- $ 在传输大量数据时，CPU 只用指示 DMA 进行传输，减少了 CPU 占用

计算题

Assume: that the number of clock cycles for a polling operation is 400 and that processor executes with a 500-Mhz clock.

Determine the fraction of CPU time consumed for the mouse, floppy disk, and hard disk.

We assuming that you poll often enough so that no data is ever lost and that those devices are potentially always busy.

We assume again that:

1. The mouse must be polled 30 times per second to ensure that we do not miss any movement made by the user.

2. The floppy disk transfers data to the processor in 16-bit units and has a data rate of 50 KB/sec. No data transfer can be missed.

3. The hard disk transfers data in four-word chunks and can transfer at 4 MB/sec. Again, no transfer can be missed.

Suppose we have the same hard disk and processor we used in the former example, but we used interrupt-driven I/O. The overhead for each transfer, including the interrupt, is 500 clock cycles. Find the fraction of the processor consumed if the hard disk is only transferring data 5% of the time.

Suppose we have the same hard disk and processor we used in the former example.

Assume that the initial setup of a DMA transfer takes 1000 clock cycles for the processor, and assume the handling of the interrupt at DMA completion requires 500 clock cycles for the processor.

The hard disk has a transfer rate of 4MB/sec and uses DMA. The average transfer from disk is 8 KB. Assume the disk is actively transferring 100% of the time.

Please find what fraction of the processor time is consumed.

> 这几道题是为了证明，interrupt with DMA > interrupt > polling
> 虽然题目中疑似 polling 进行连续数据传输会更快，这是因为 interrupt 会有 overhead；但是在数据访问频率很低或访问数据很少的时候，interrupt 效率会更高，这是因为 polling 为了不丢失数据总是需要高频问询

5 I/O System

> 找到 I/O 瓶颈

Question

Consider the following computer system:

1. A CPU sustains 3 billion instructions per second and it takes average *100,000* instructions in the operating system per I/O operation.
2. A memory backplane bus is capable of sustaining a transfer rate of 1000 MB/sec.
3. SCSI-Ultra320 controllers with a transfer rate of 320 MB/sec and accommodating up to 7 disks.
4. Disk drives with a read/write bandwidth of 75 MB/sec and an average seek plus rotational latency of 6 ms.

If the workload consists of 64-KB reads (assuming the data block is sequential on a track), and the user program need *200,000* instructions per I/O operation, please find the maximum sustainable I/O rate and the number of disks and SCSI controllers required.