Operating Systems
I/0 devices

Nipun Batra

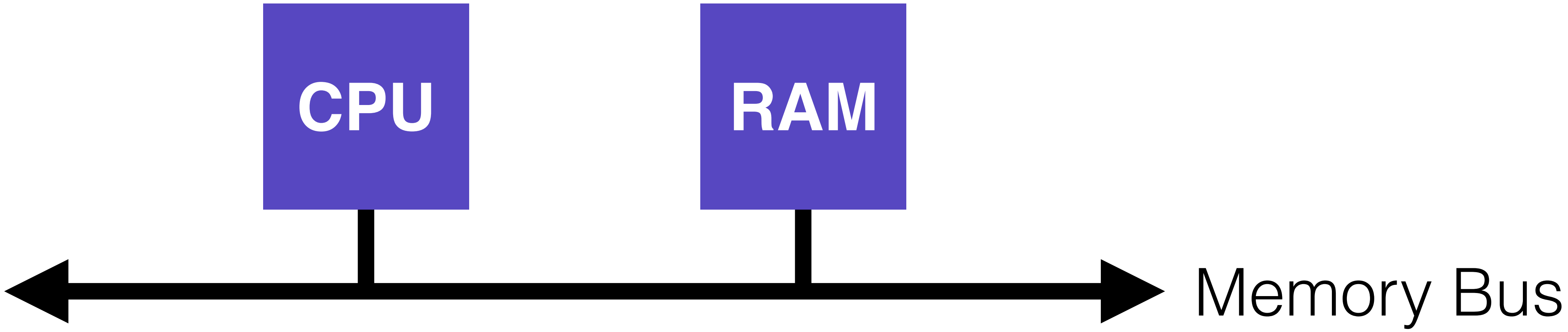
Motivation

What good is a computer without any I/O devices?
- keyboard, display, disks

We want:
- **H/W** that will let us plug in different devices
- **OS** that can interact with different combinations

Largely a communication problem…

System Architecture



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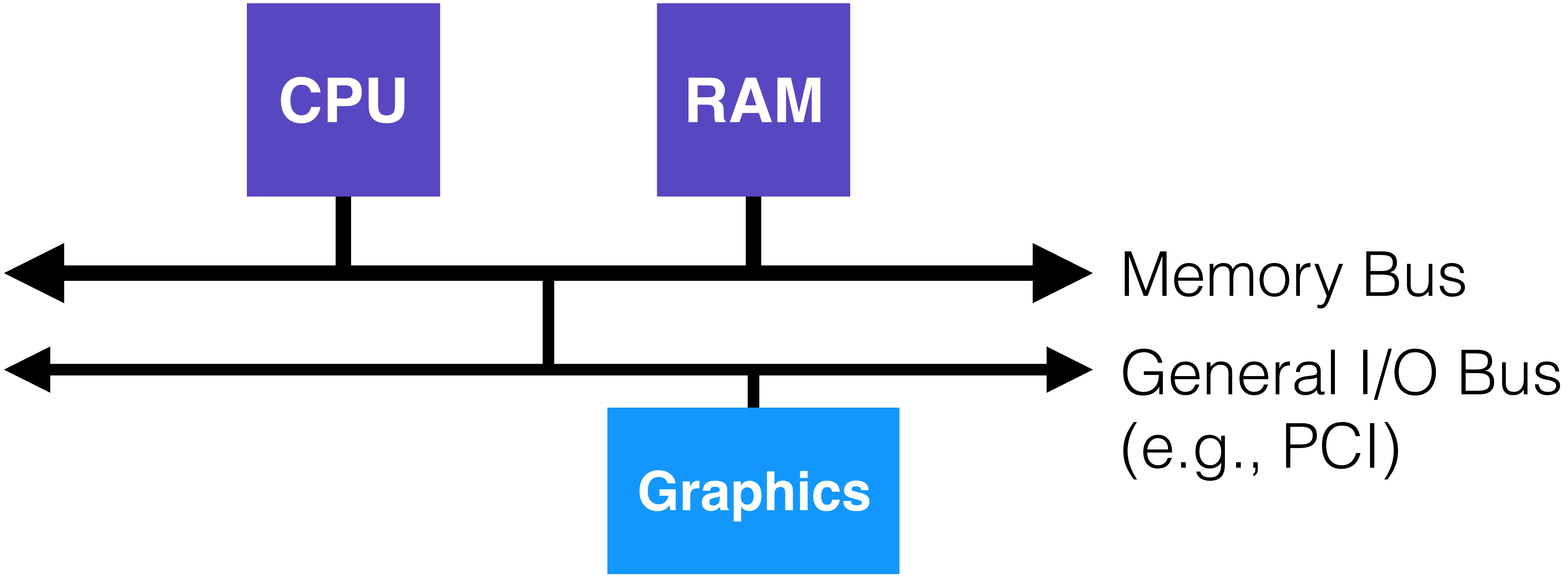

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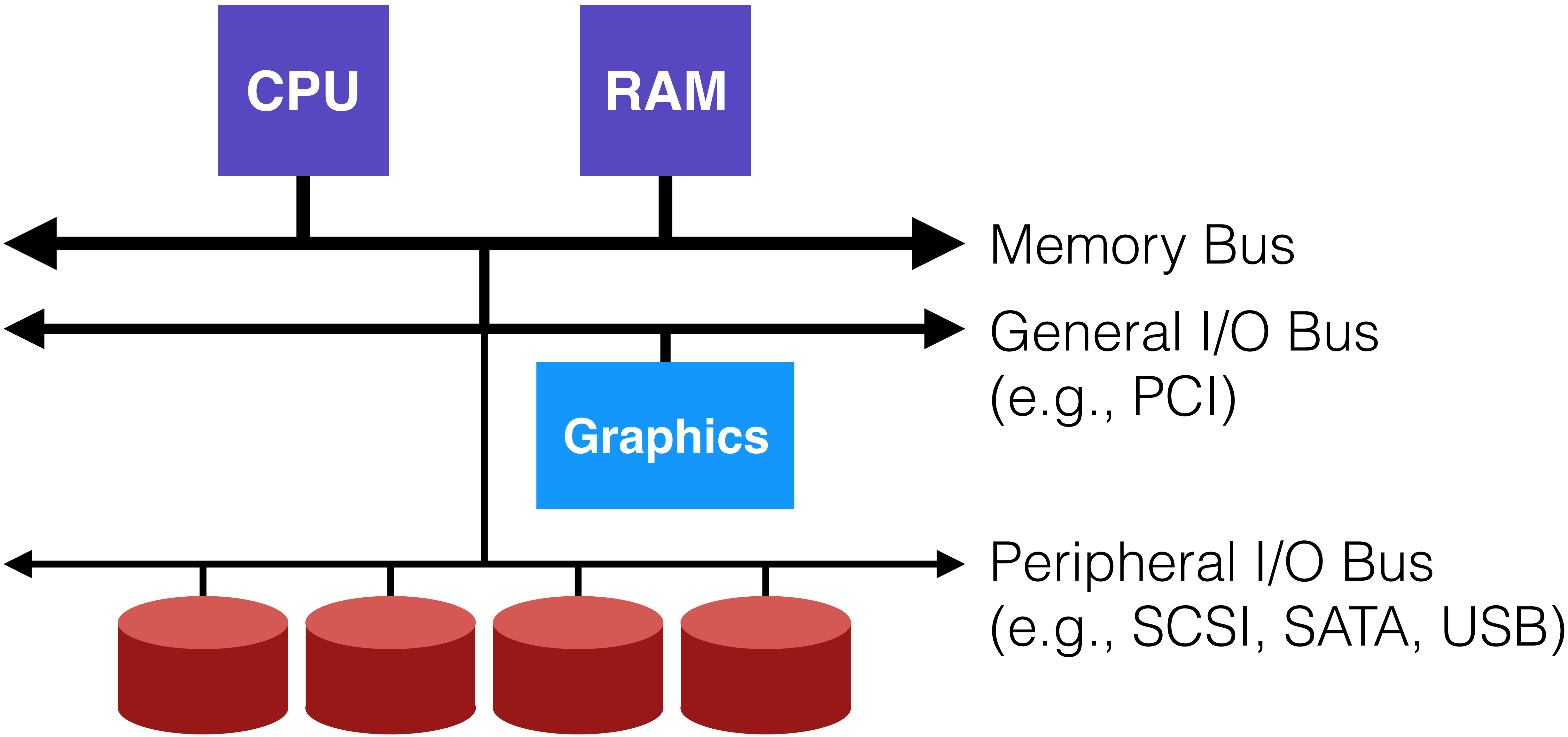

Why use hierarchical buses?

Canonical Device

Device Registers:

Canonical Device

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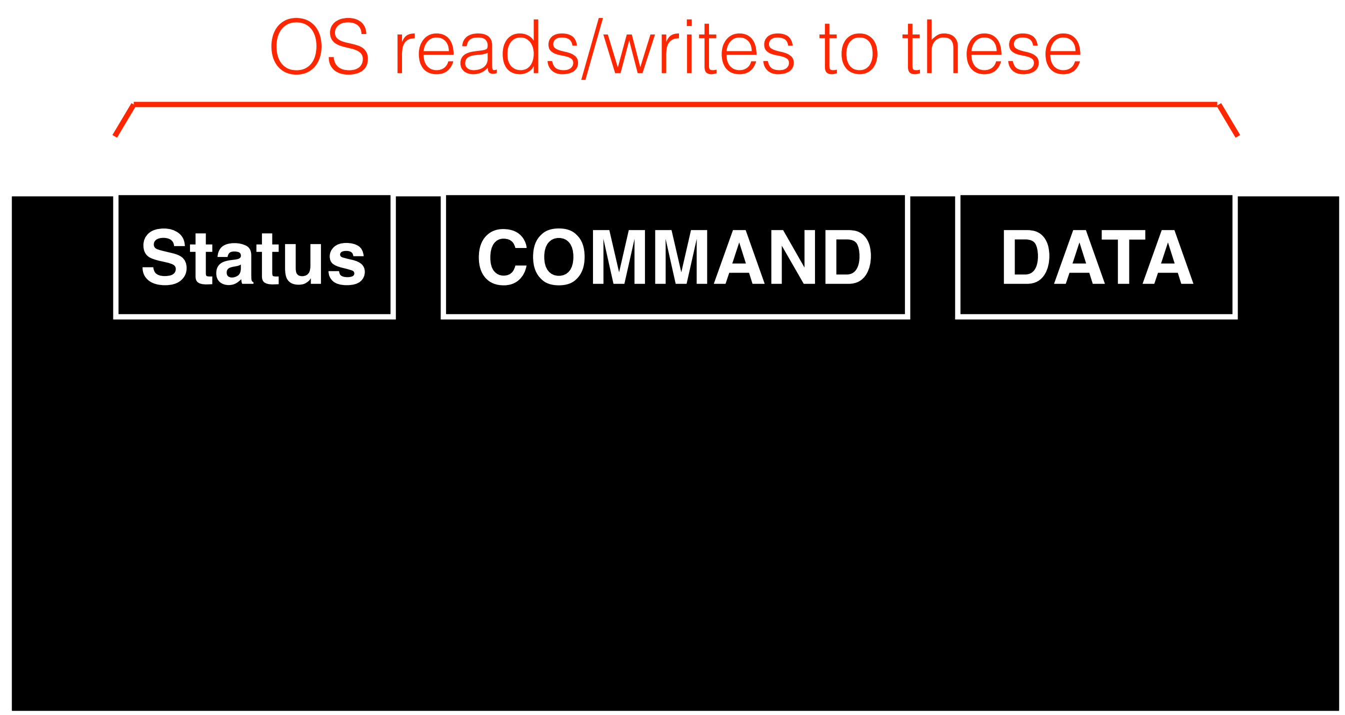

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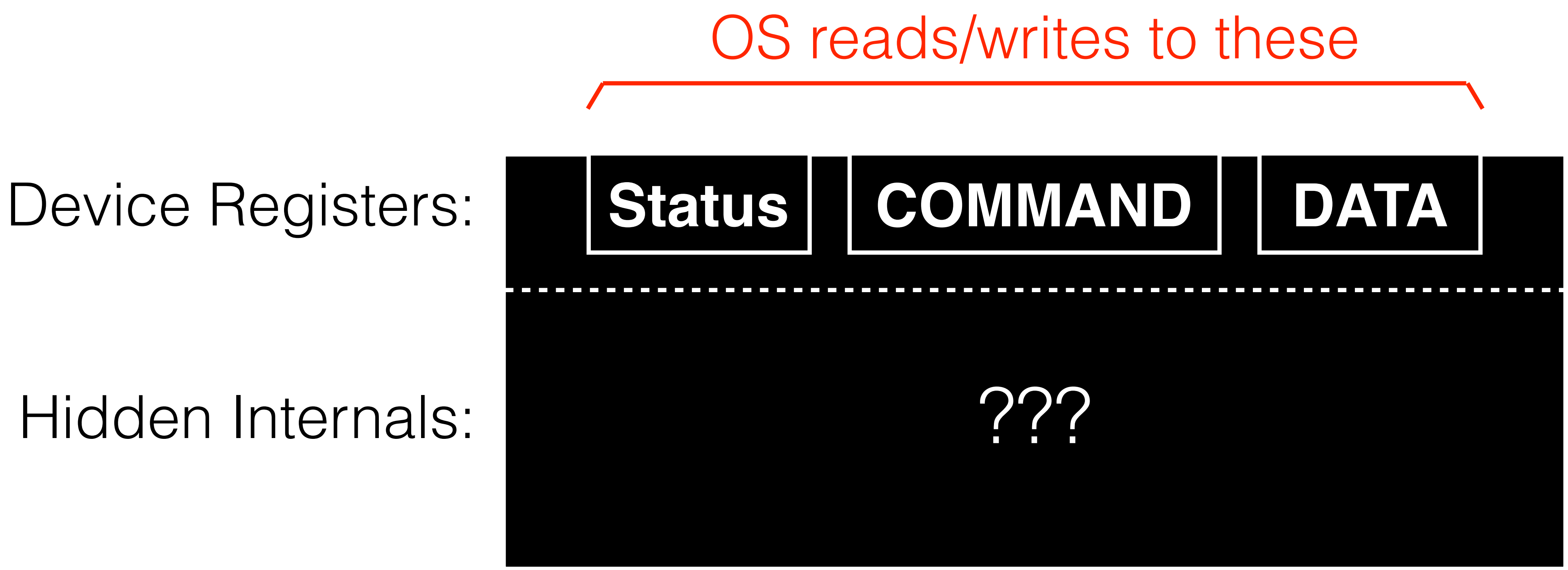

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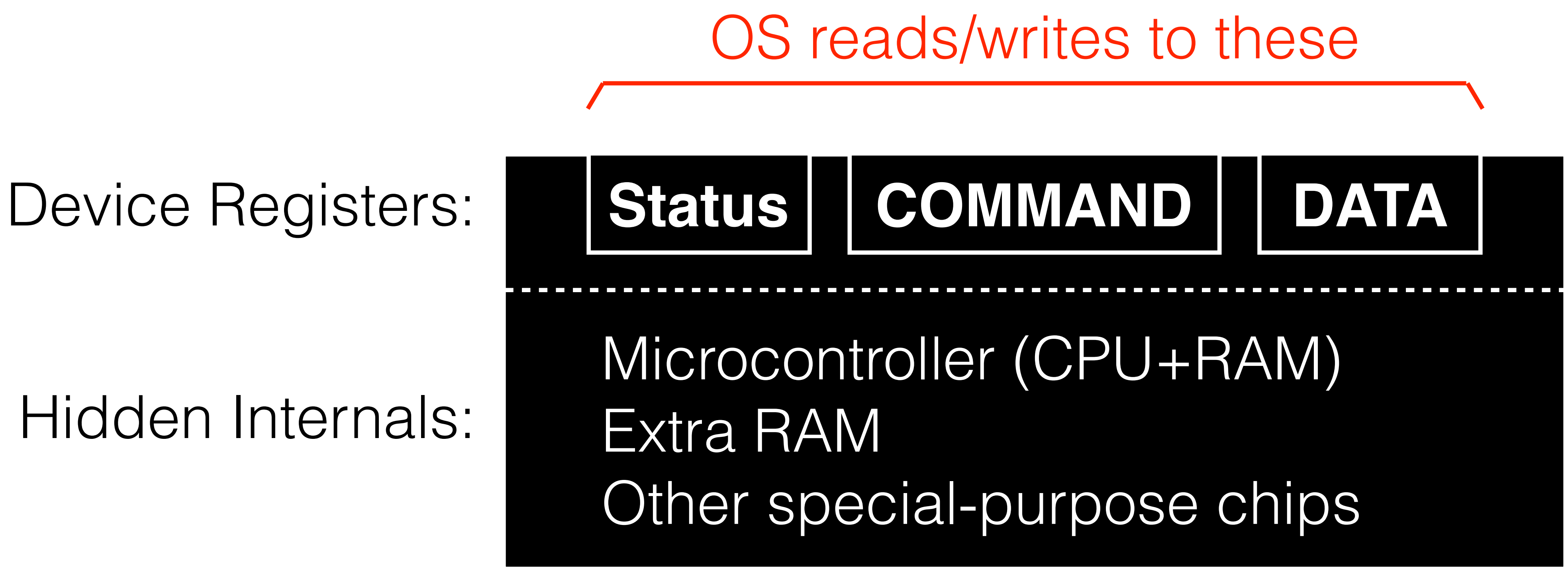

Example Protocol

```
while (STATUS == BUSY)
   ; // spin
Write data to DATA register
Write command to COMMAND register
while (STATUS == BUSY)
   ; // spin
```

Example

CPU:

Disk:

```
while (STATUS == BUSY)                  // 1
   ;
Write data to DATA register             // 2
Write command to COMMAND register       // 3
while (STATUS == BUSY)                  // 4
   ;
```

Example

CPU: **A**

Disk: **C**

```
while (STATUS == BUSY)                // 1
   ;
Write data to DATA register           // 2
Write command to COMMAND register     // 3
while (STATUS == BUSY)                // 4
   ;
```

Example

A wants to do I/O

CPU: A

Disk: C

```
while (STATUS == BUSY)                    // 1
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Write data to DATA register               // 2
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```
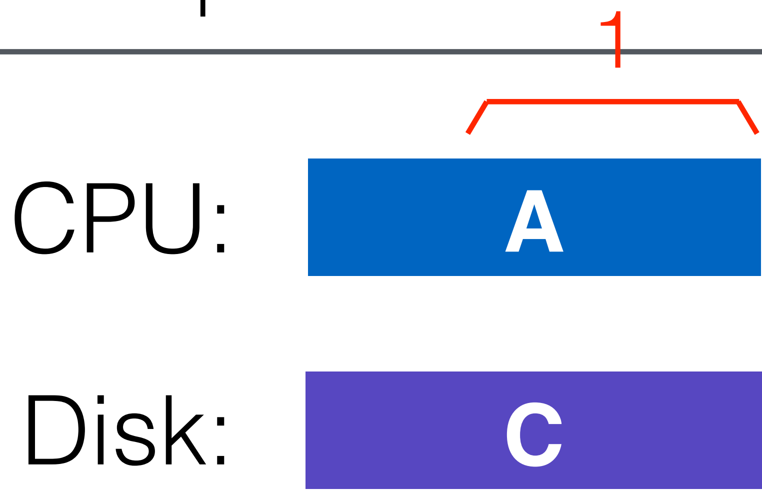

Example

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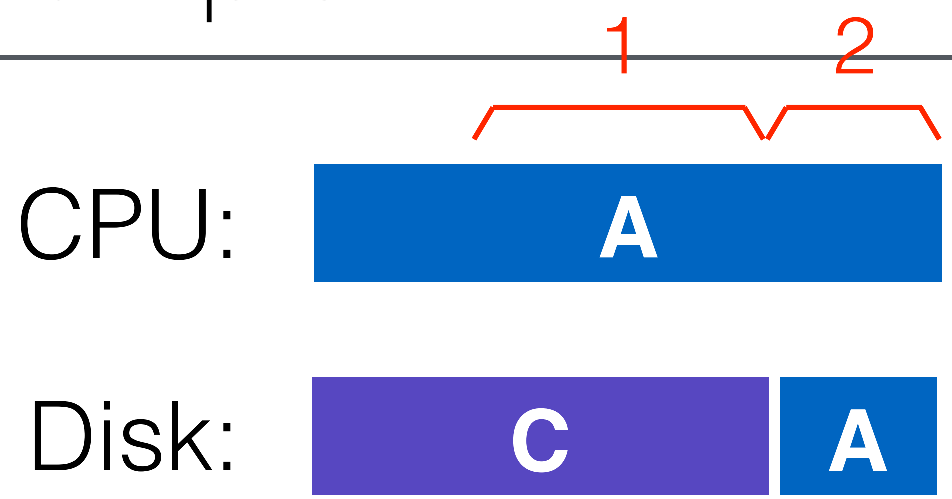


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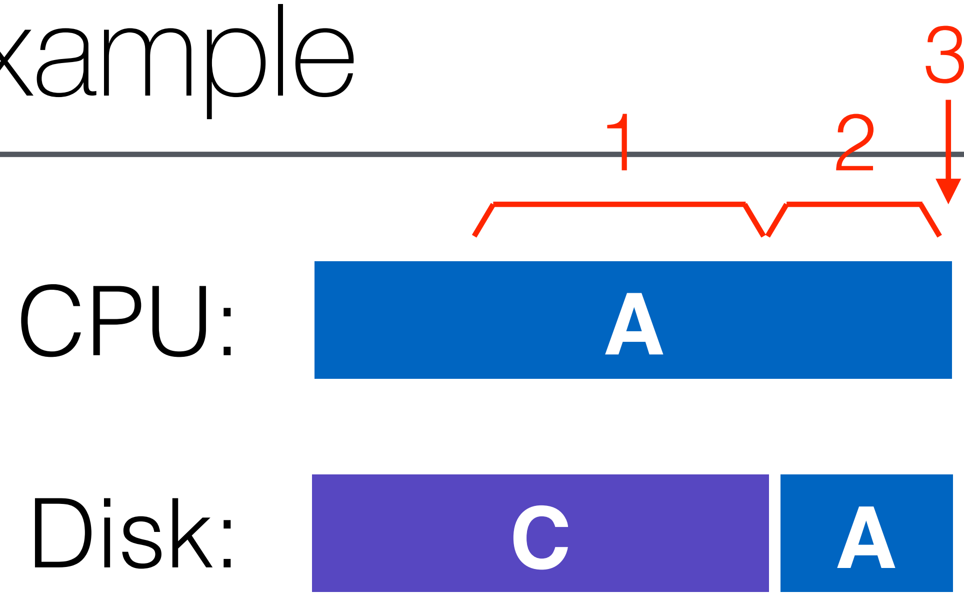


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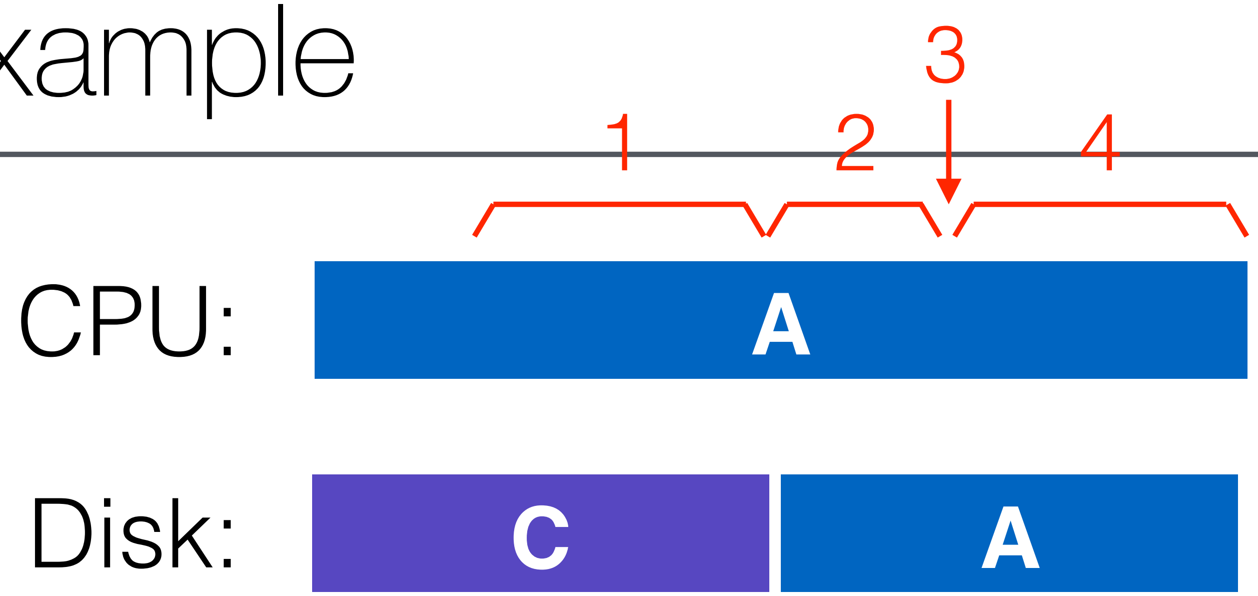


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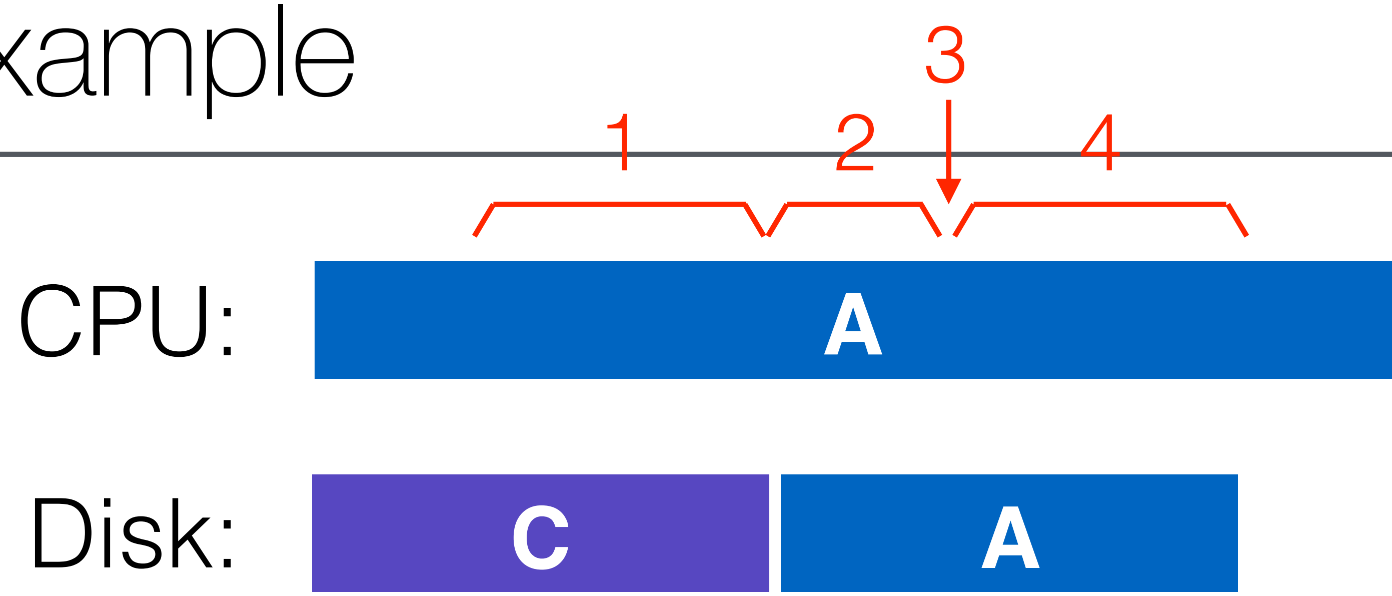


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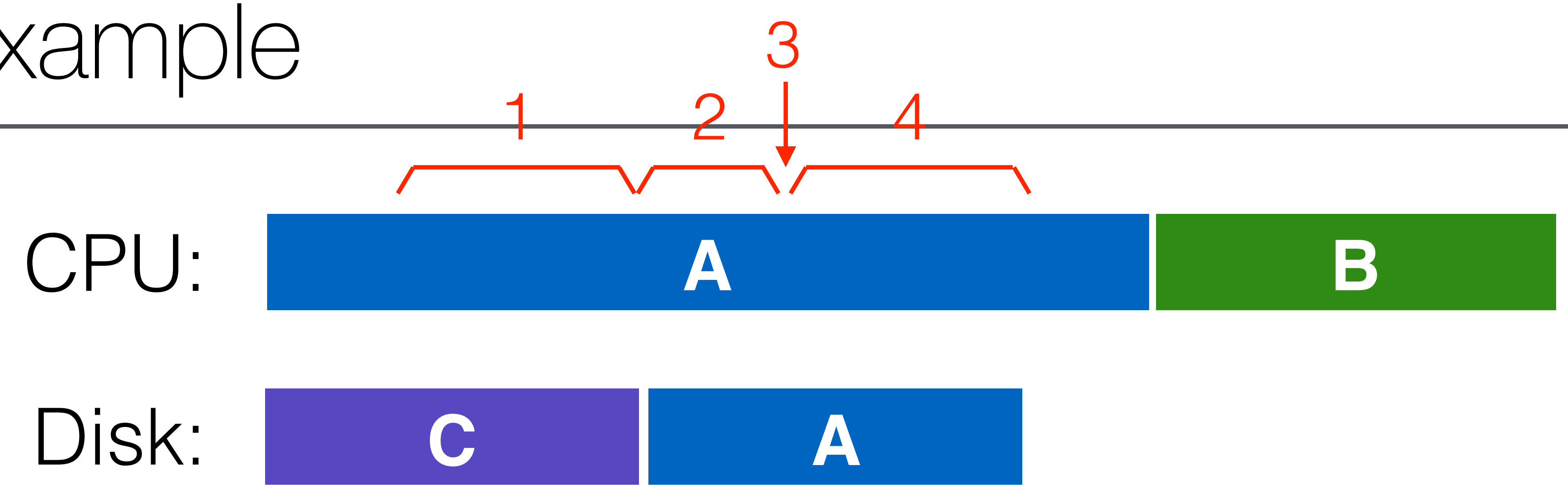


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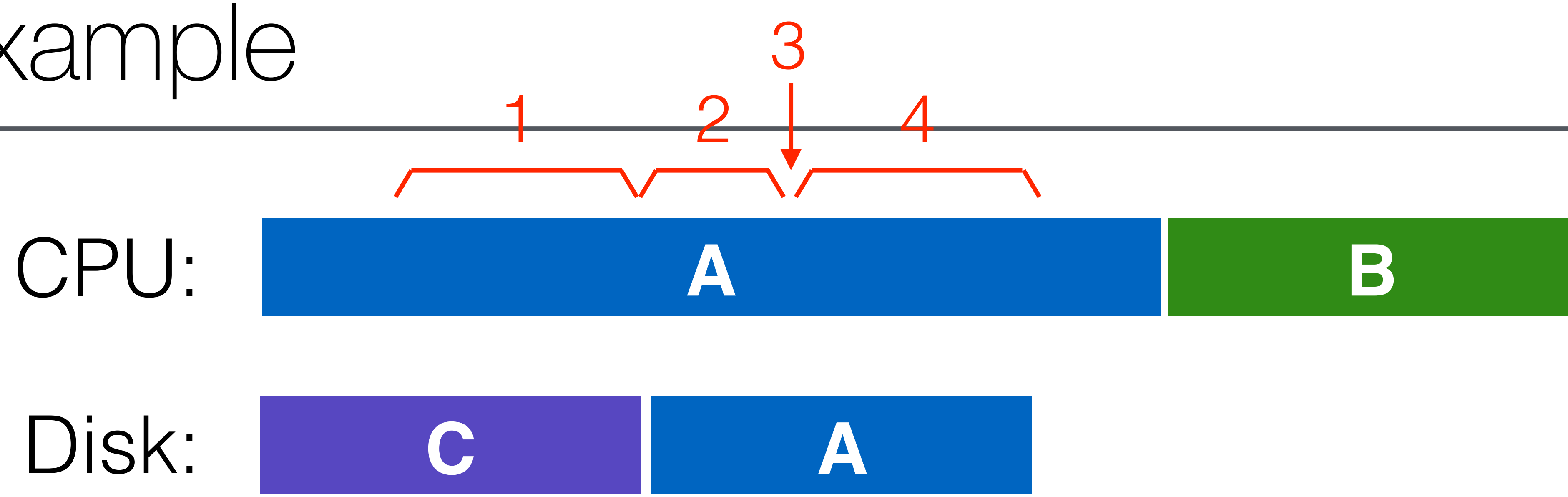


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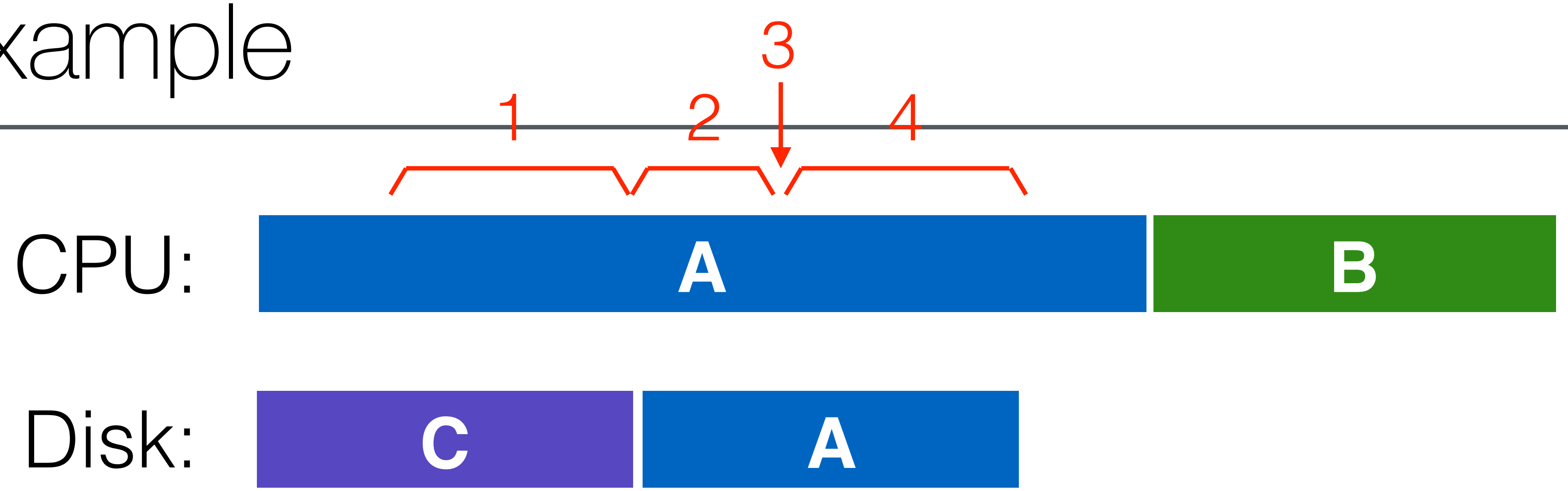
How to avoid spinning?

Example

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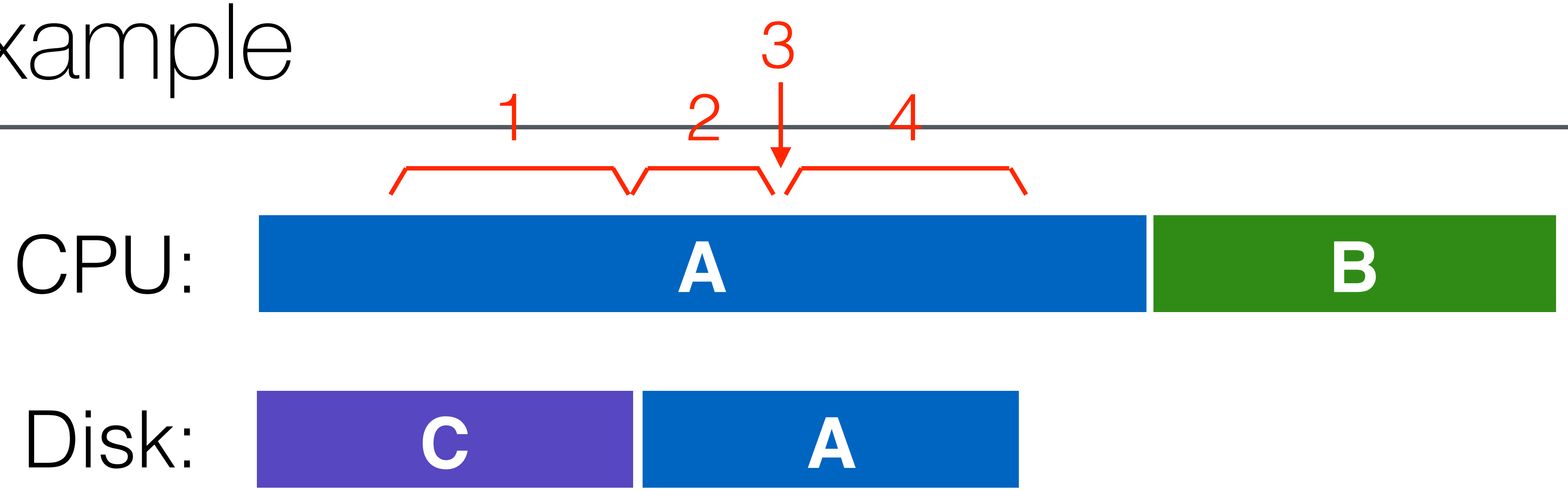
How to avoid spinning?
Interrupts!

Example




```
while (STATUS == BUSY)                 // 1
   wait for interrupt;
Write data to DATA register            // 2
Write command to COMMAND register      // 3
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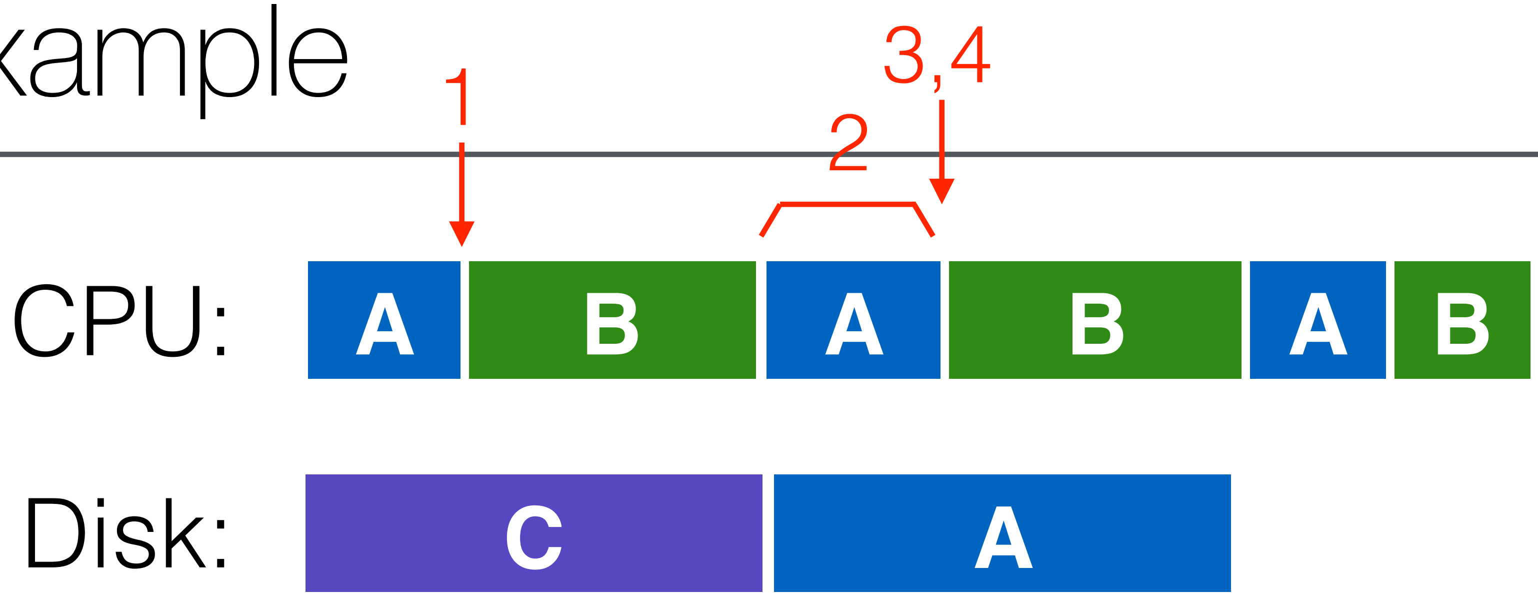
Example

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Interrupts vs. Polling

Discuss: are interrupts ever worse?

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    - interrupt coalescing

Interrupts vs. Polling

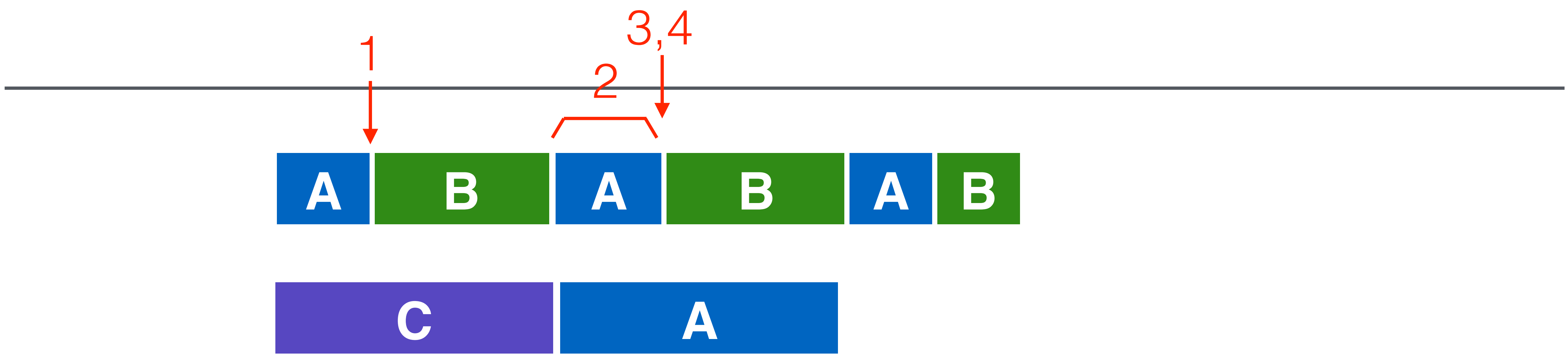
- Discuss: are interrupts ever worse?
- Interrupts can sometimes lead to livelock
    - e.g., flood of network packets
- Techniques:
    - hybrid approach
        - Poll for a while, then wait for interrupts
    - interrupt coalescing
        - Coalesce or combine the delivery of multiple interrupts

Protocol Variants

Status checks: polling *vs.* interrupts

Data: PIO *vs.* DMA

Control: special instructions *vs.* memory-mapped I/O

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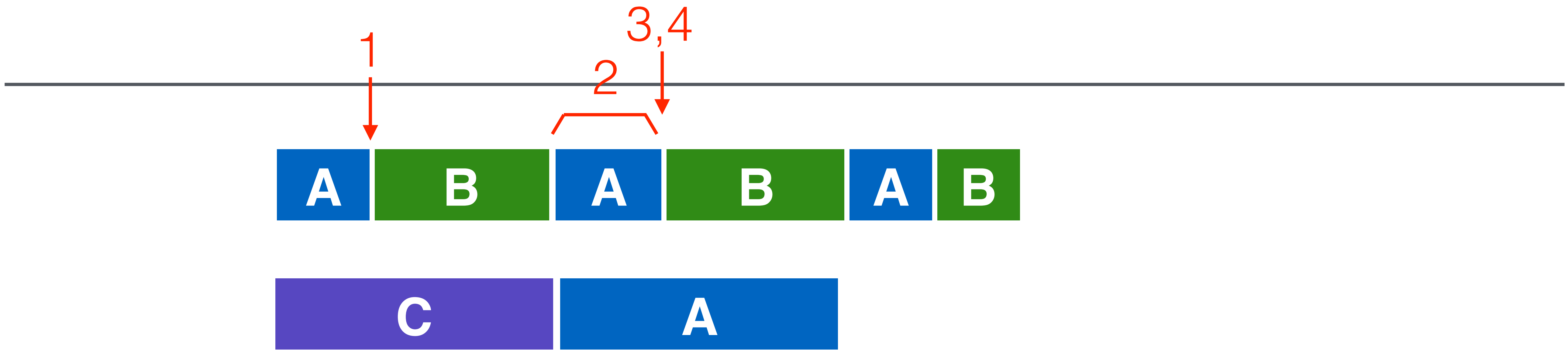


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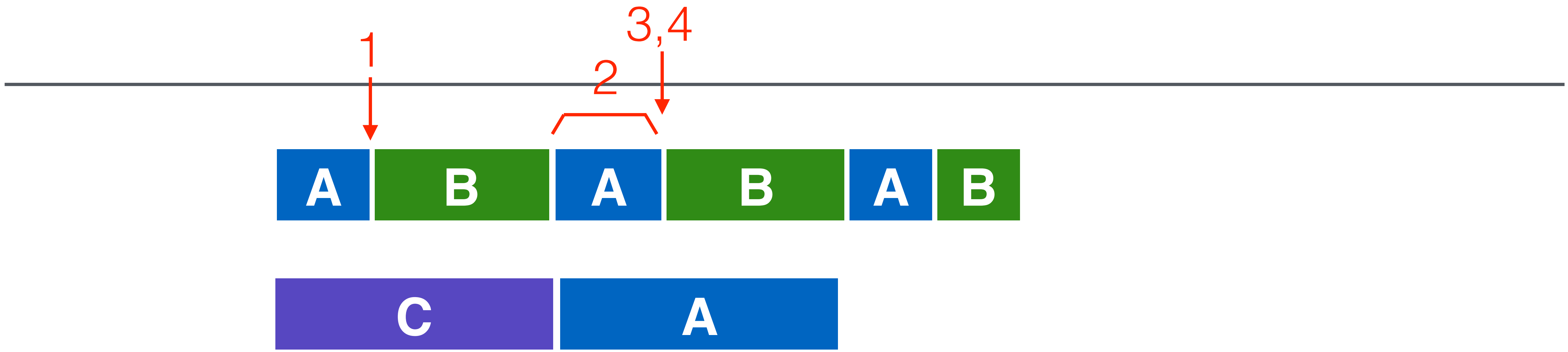


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while (STATUS == BUSY)              // 1
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```
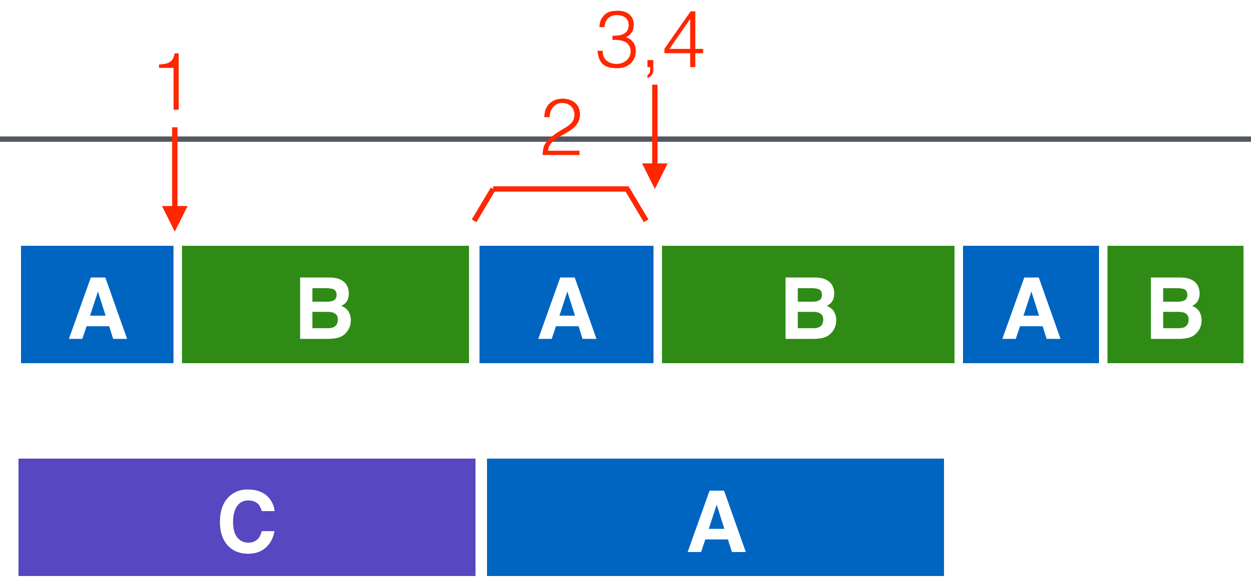

What else can we optimize?

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   wait for interrupt;
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What else can we optimize?

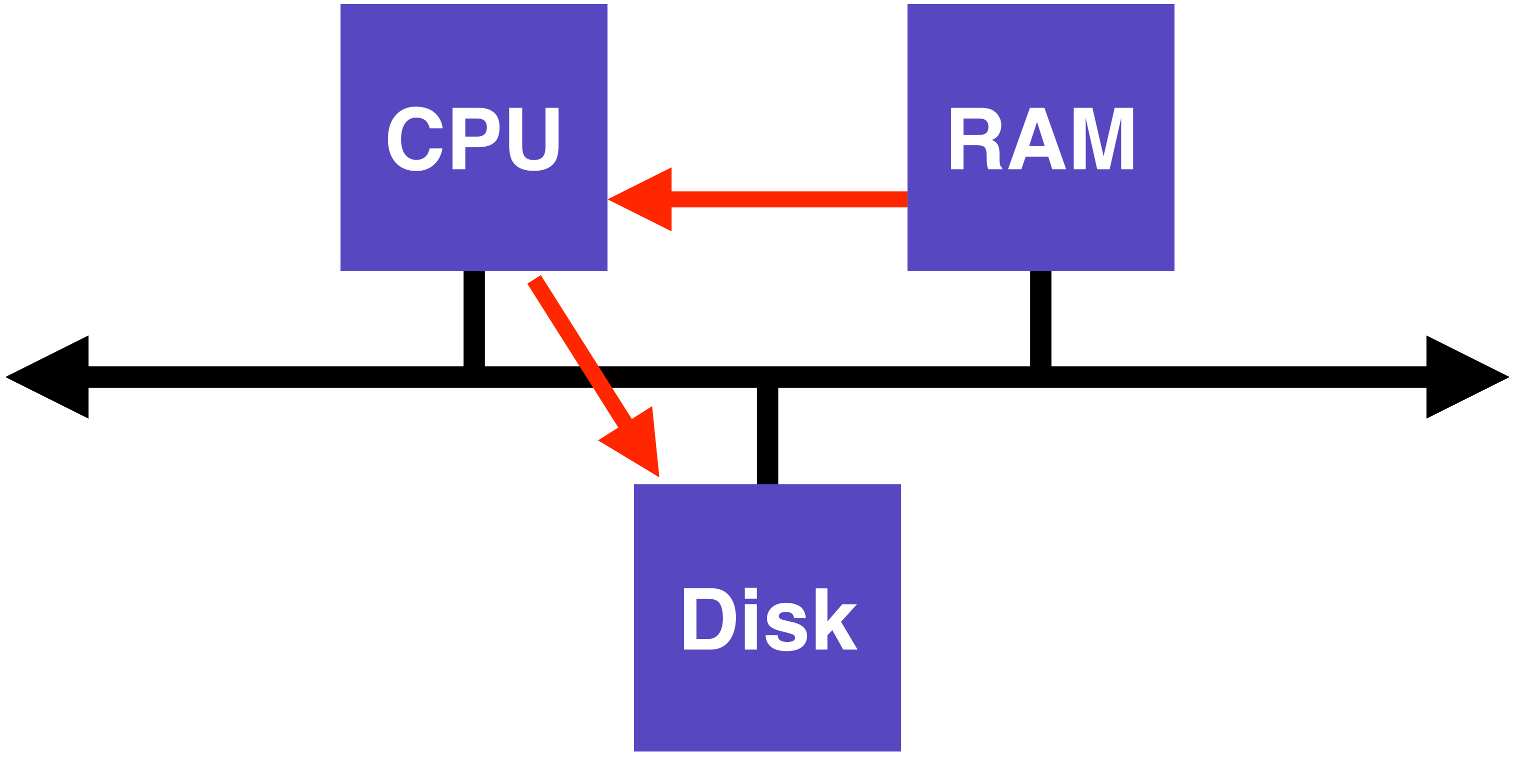
Data transfer!

Programmed I/O vs. Direct Memory Access

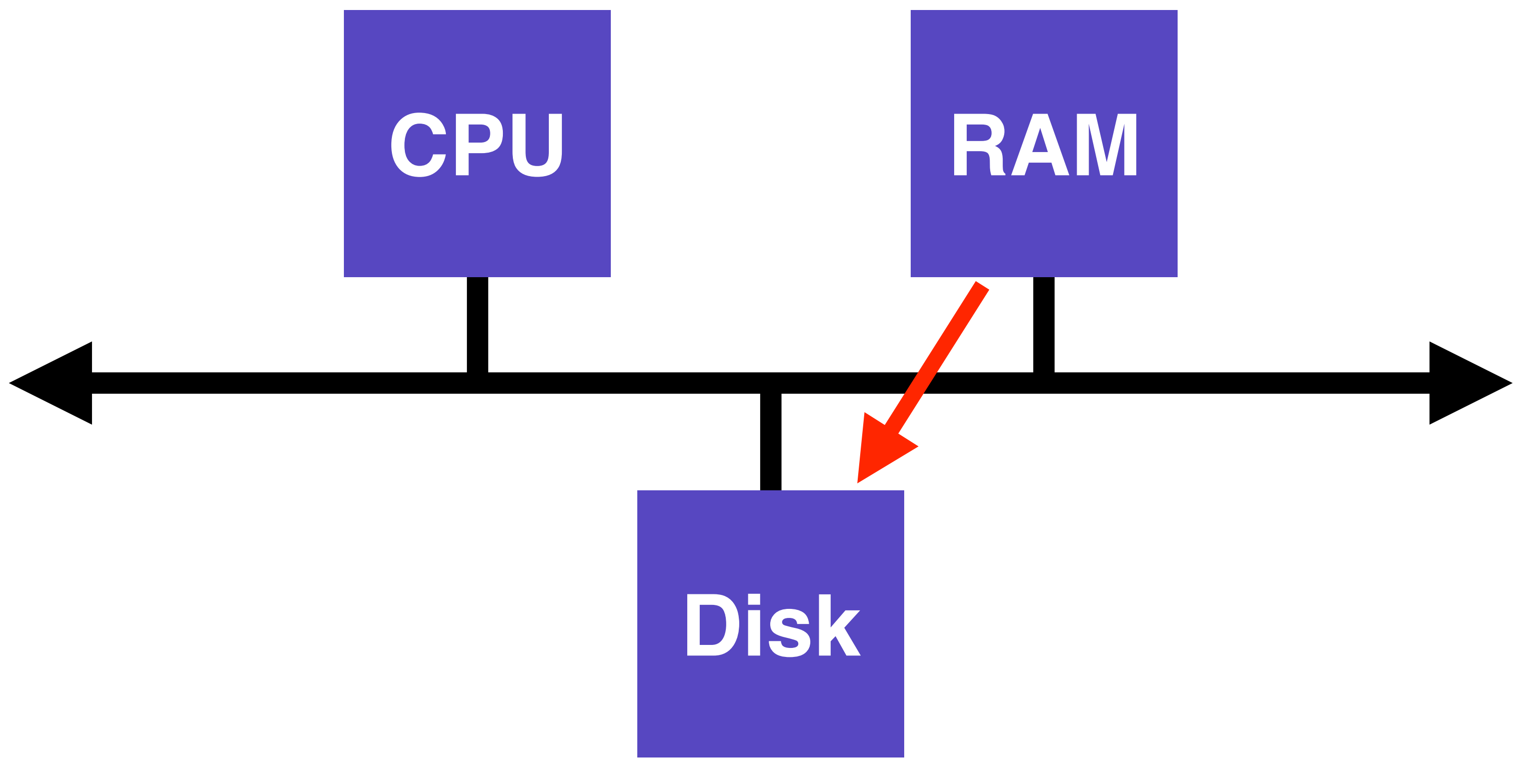
PIO (Programmed I/O):
- CPU directly tells device what data is

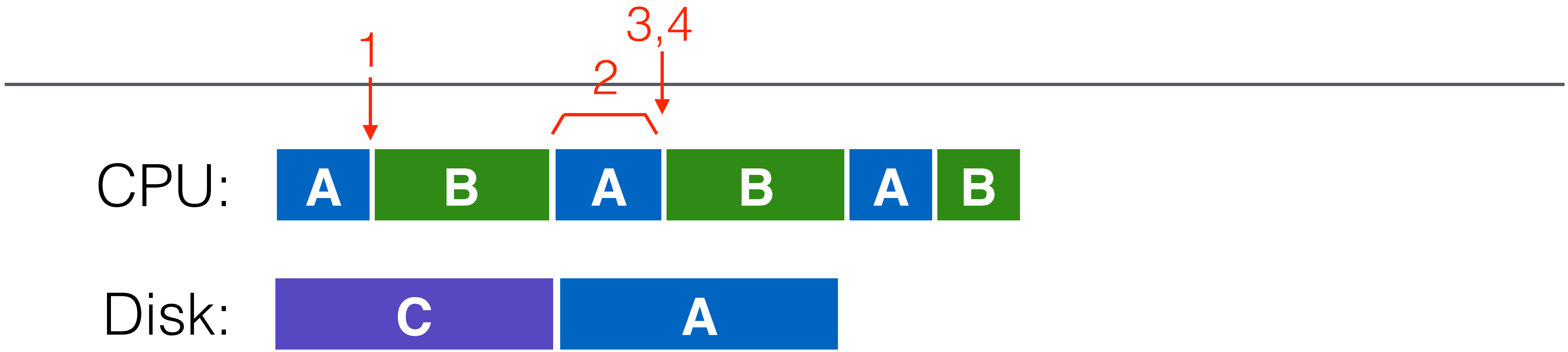
DMA (Direct Memory Access):
- CPU leaves data in memory
- DMA device does copy

PIO Flow



DMA Flow



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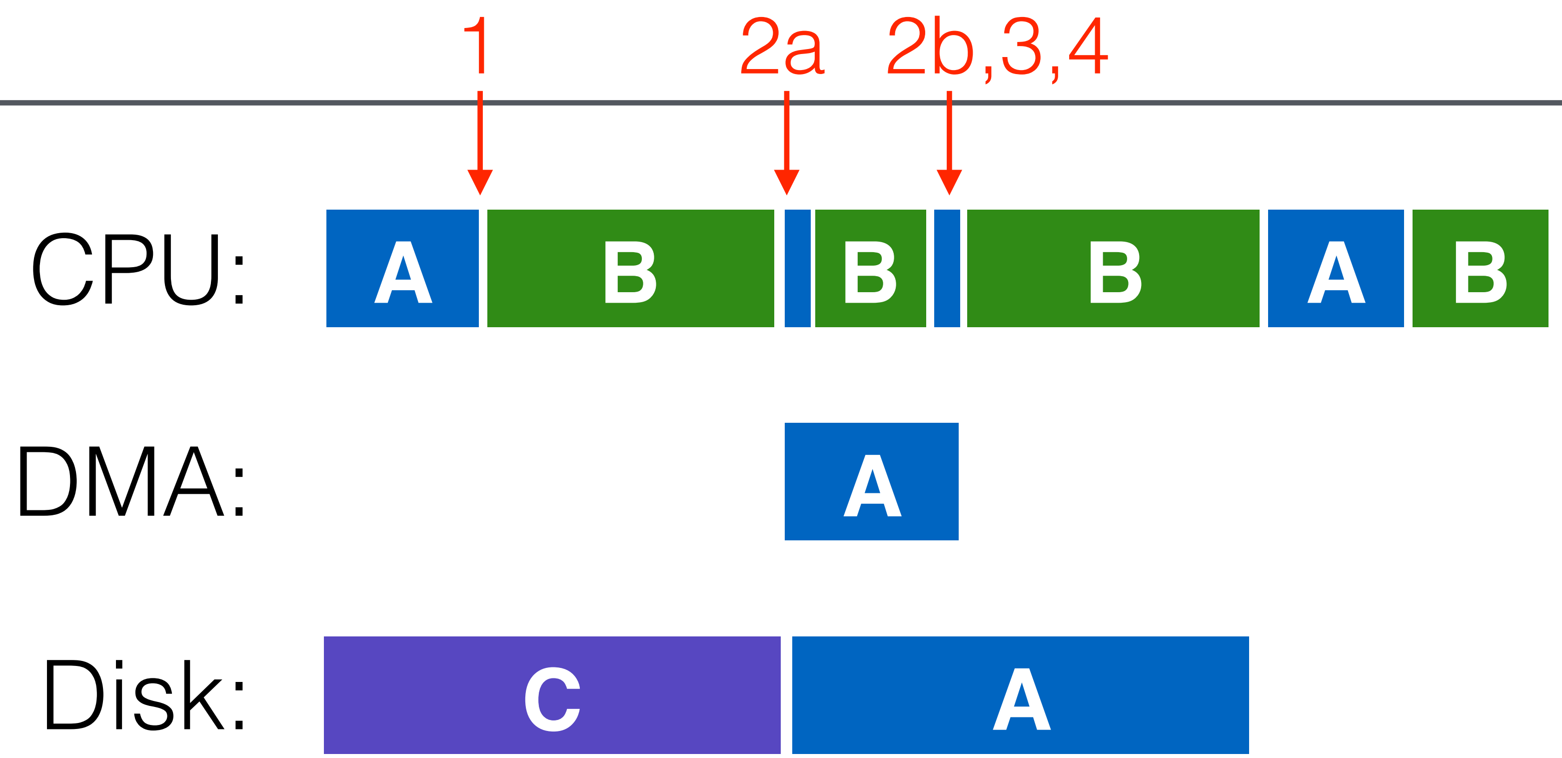


```
while (STATUS == BUSY)                // 1
   wait for interrupt;
initiate DMA transfer                 // 2a
wait for interrupt                    // 2b
Write command to COMMAND register     // 3
while (STATUS == BUSY)                // 4
   wait for interrupt;
```

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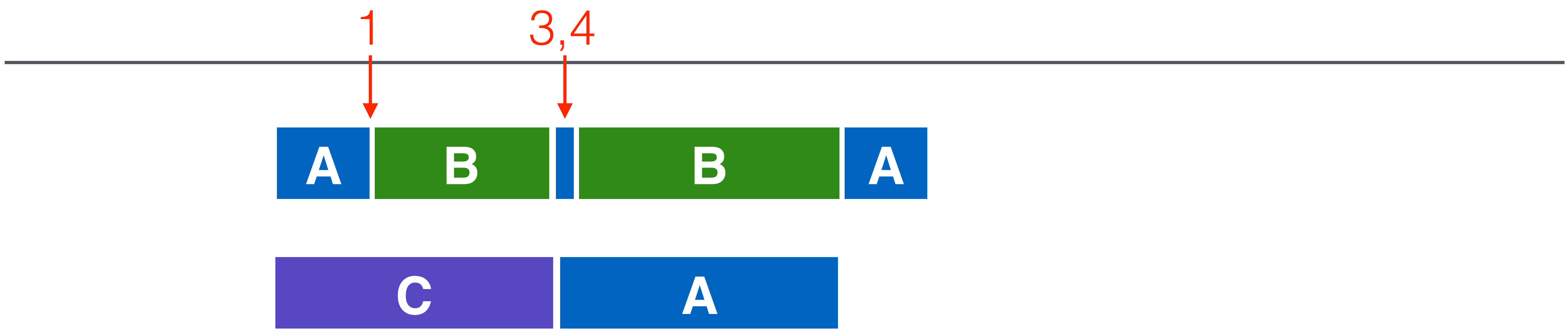


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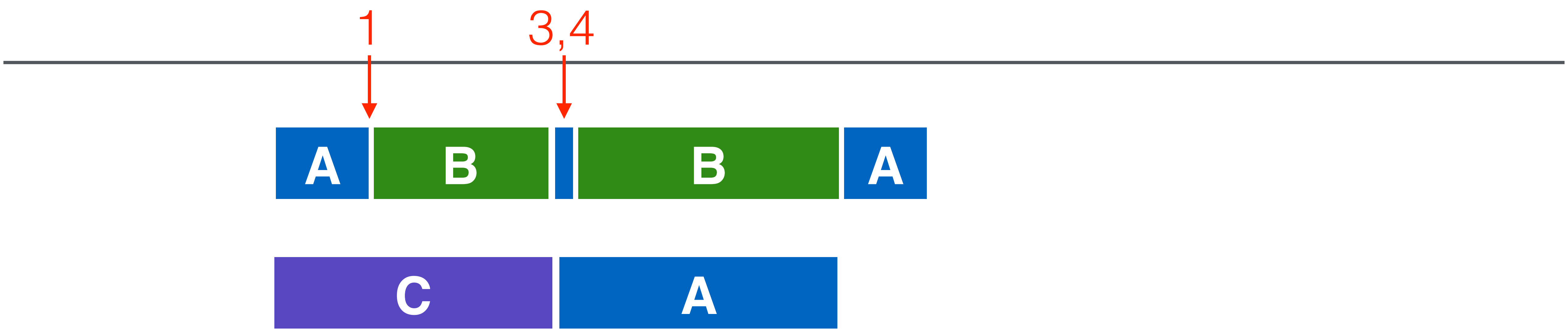


```
while (STATUS == BUSY)                  // 1
  wait for interrupt;
~~Write data to DATA register~~         // 2
Write command to COMMAND register       // 3
while (STATUS == BUSY)                  // 4
  wait for interrupt;
```

How does OS read and write registers?

Special Instructions vs. Mem-Mapped I/O

Special instructions
- each device has a port
- in/out instructions (x86) communicate with device

Memory-Mapped I/O
- H/W maps registers into address space
- loads/stores sent to device

Doesn't matter much (both are used).

Variety is a Challenge

Problem:
- many, many devices
- each has its own protocol

How can we avoid writing a slightly different OS for each H/W combination?

Solution

Encapsulation!

Write driver for each device.

Drivers are **70%** of Linux source code.

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Write driver for each device.

Drivers are **70%** of Linux source code.

Encapsulation also enables us to mix-and-match devices, schedulers, and file systems.

Storage Stack

application

file system

scheduler

driver

hard drive

Storage Stack

application

file system

scheduler

driver

hard drive

build common interface
on top of all HDDs

Storage Stack

what about special capabilities?

application

file system

scheduler

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build common interface on top of all HDDs

Hard-disk Basic Interface

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Disk has a sector-addressable address space

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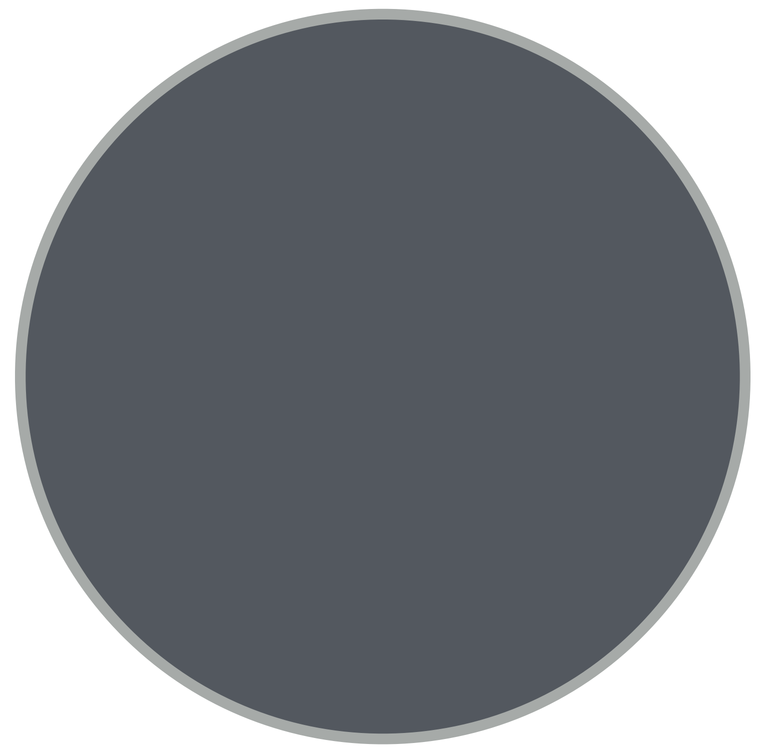
Sectors are typically 512 bytes or 4096 bytes.

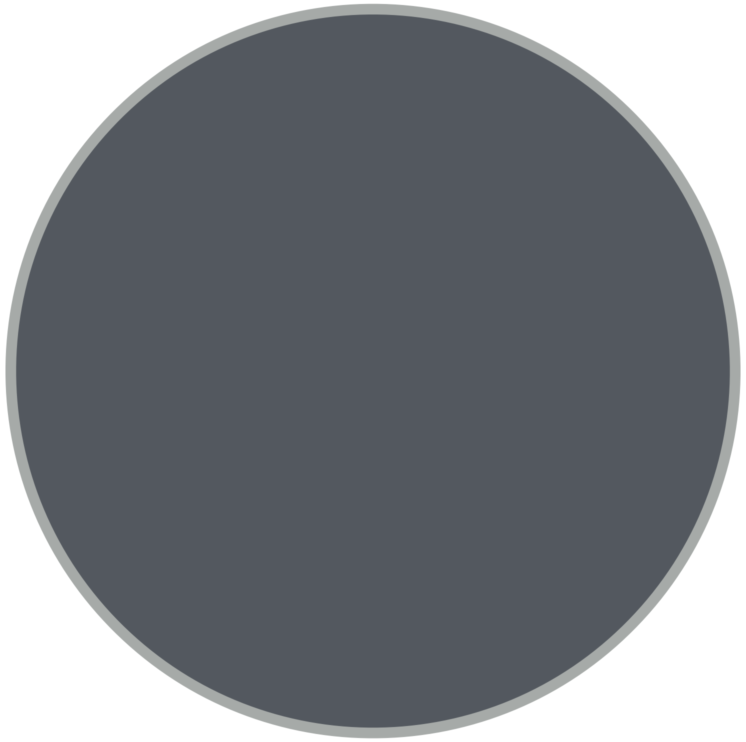
Main operations: reads + writes to sectors (blocks).

Hard-disk Basic Interface



Hard-disk Basic Interface

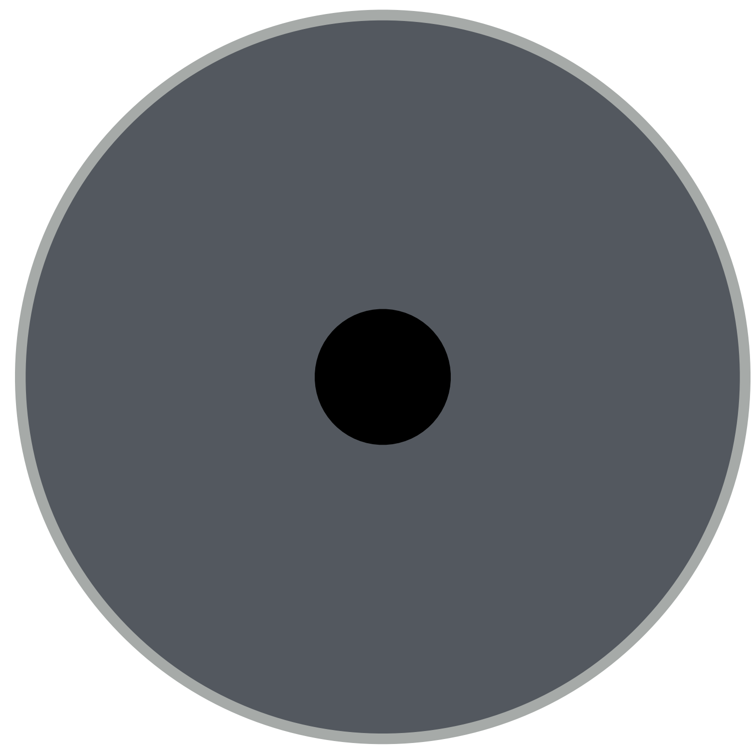
Platter



Platter is covered with a magnetic film.

Hard-disk Basic Interface

Spindle



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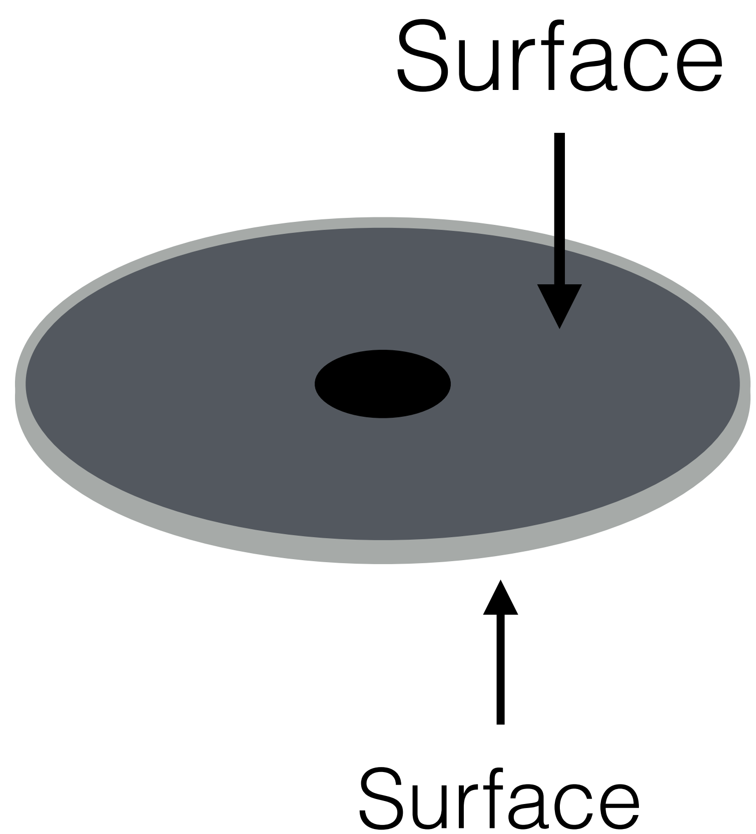

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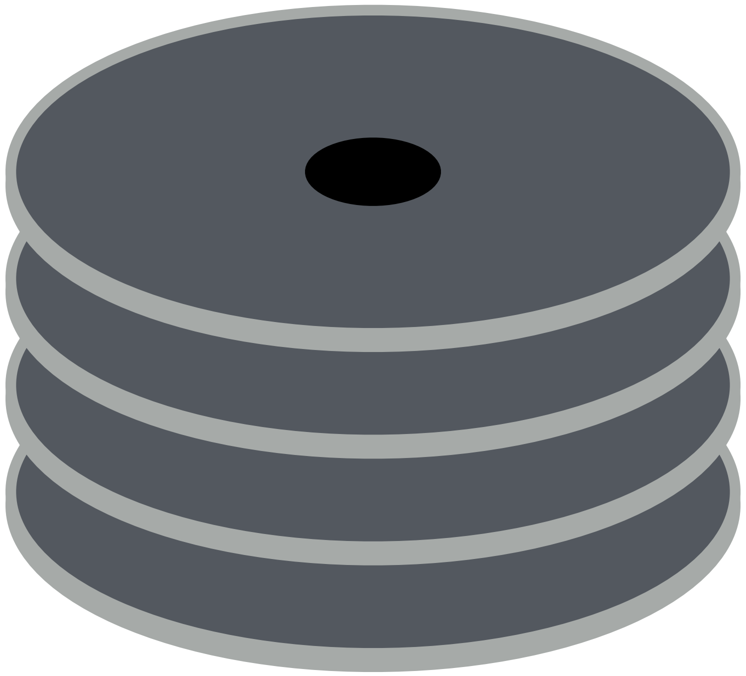
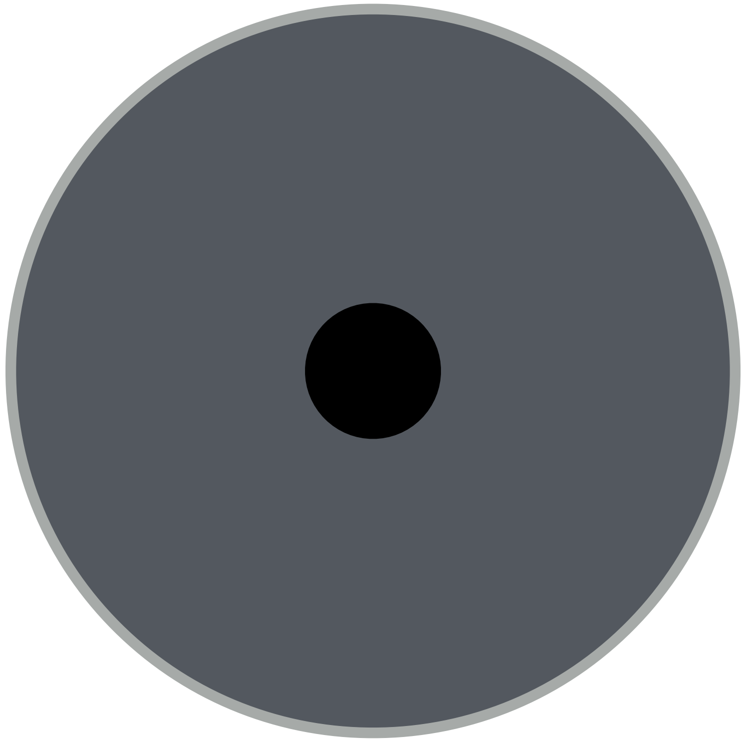


Many platters may be bound to the spindle.

Hard-disk Basic Interface



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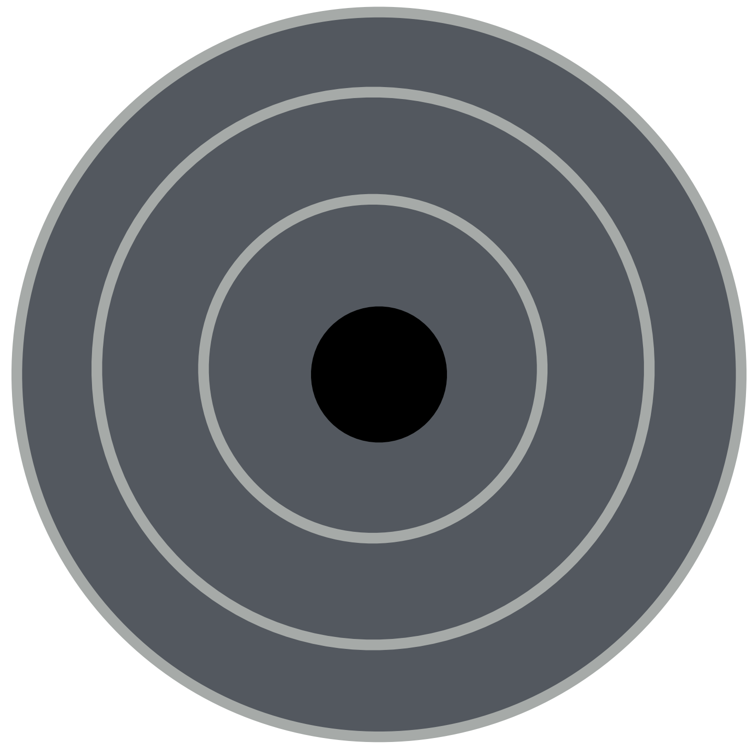
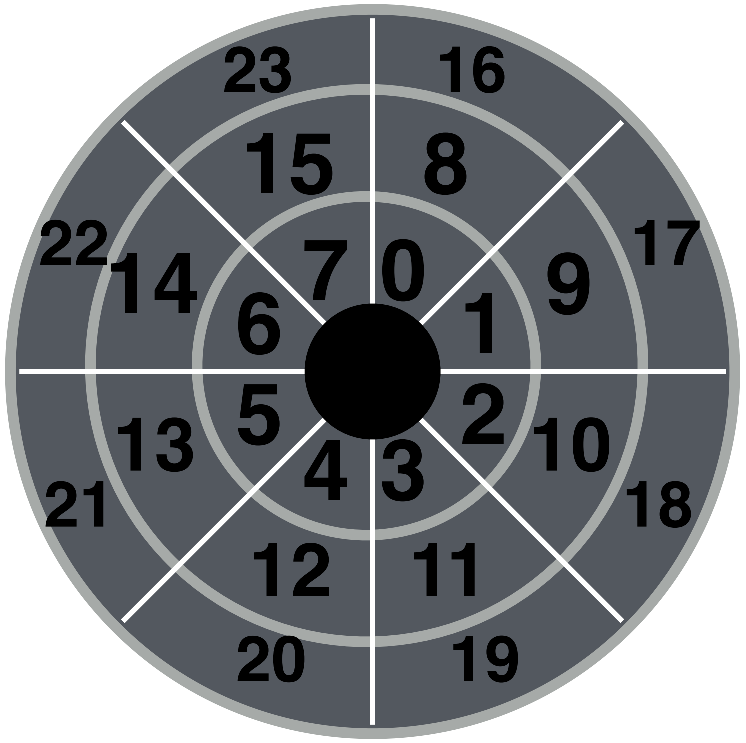


Each surface is divided into rings called <u>tracks</u>.
A stack of tracks (across platters) is called a <u>cylinder</u>.

Hard-disk Basic Interface

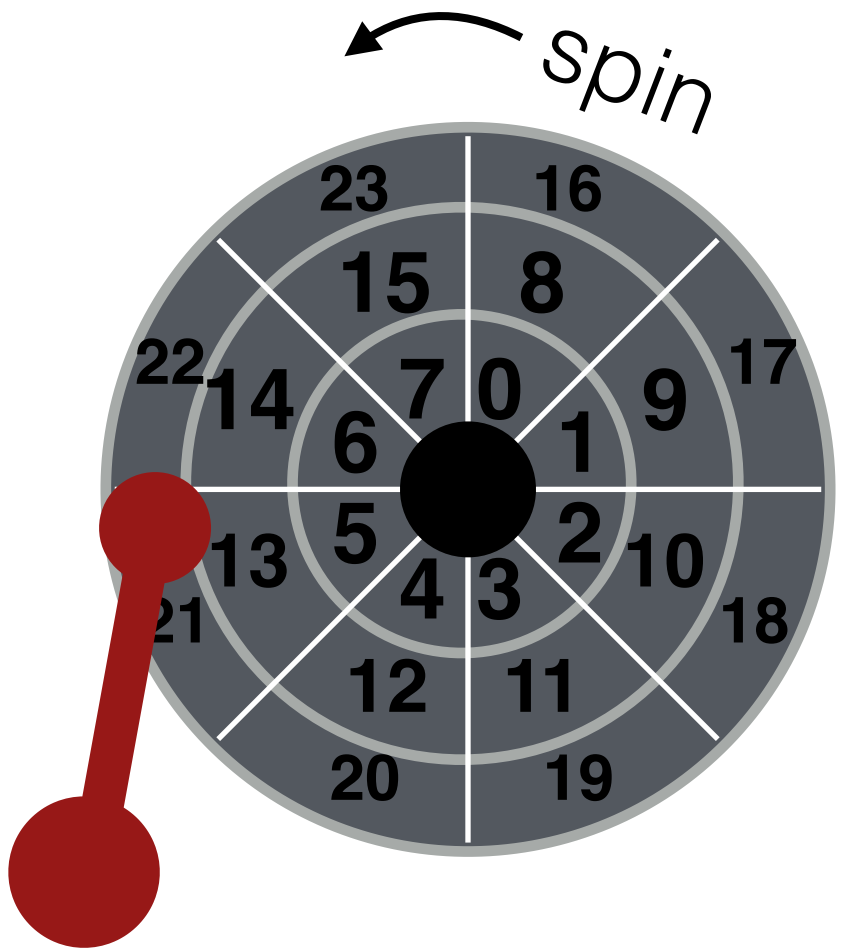


The tracks are divided into numbered sectors.

Hard-disk Basic Interface

<u>Heads</u> on a moving <u>arm</u> can read from each surface.

Hard-disk Basic Interface

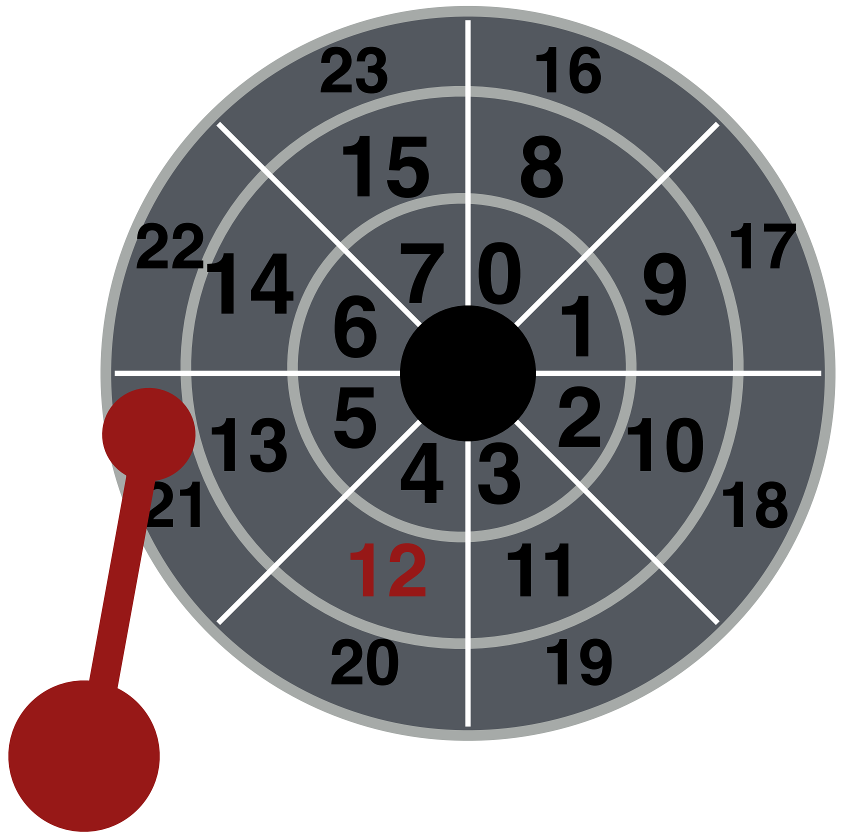


Spindle/platters rapidly spin.

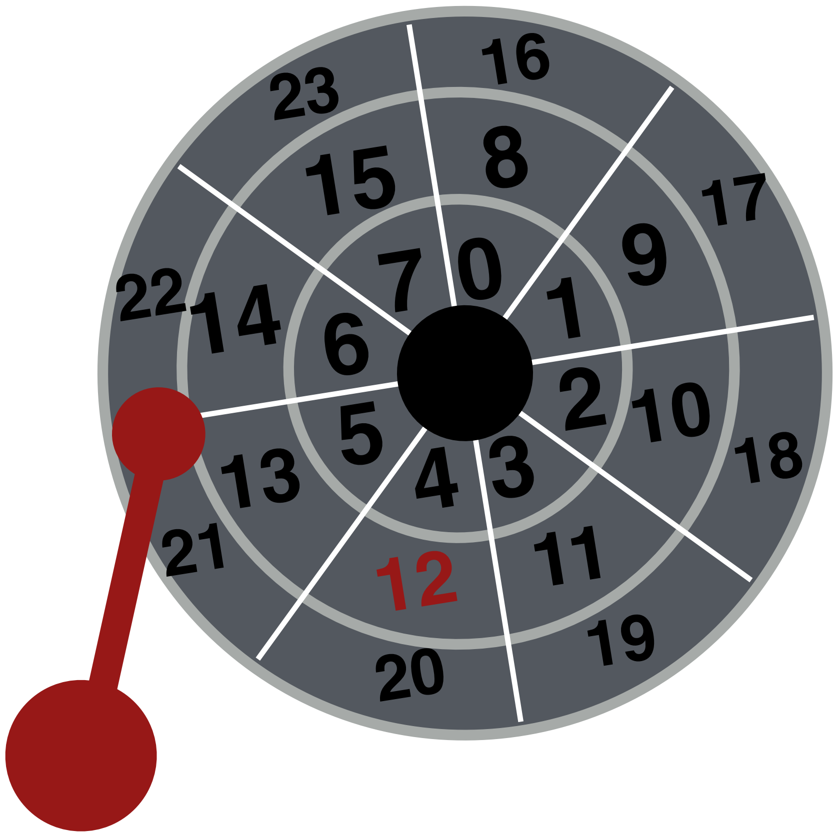
Don't try this at home!

http://youtu.be/9eMWG3fwiEU?t=30s

Let's Read 12!



Seek to right track.



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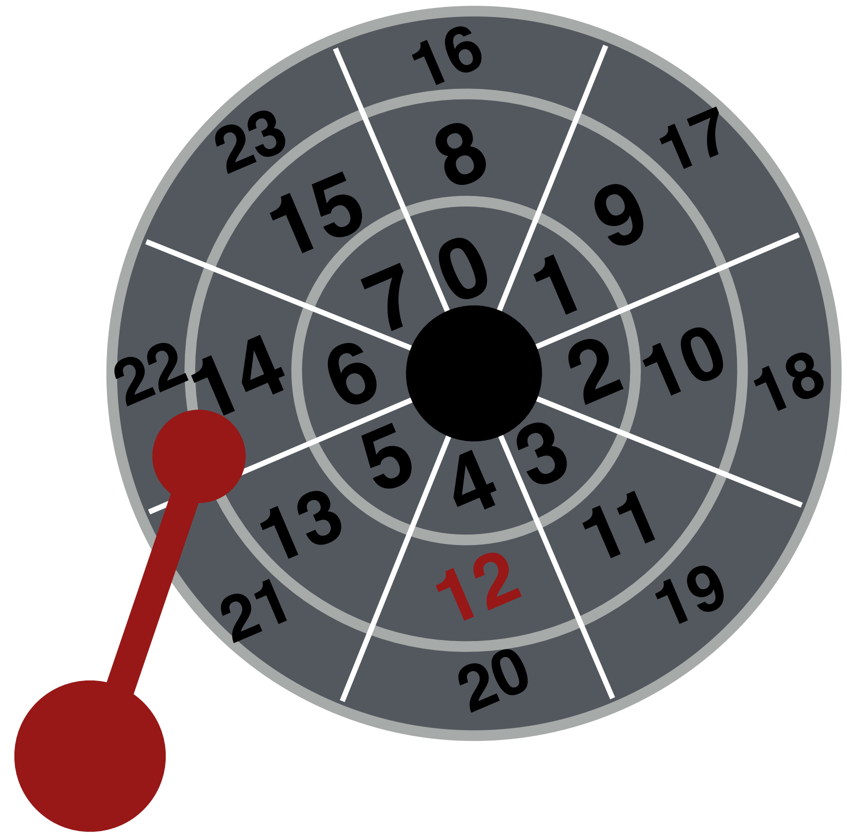

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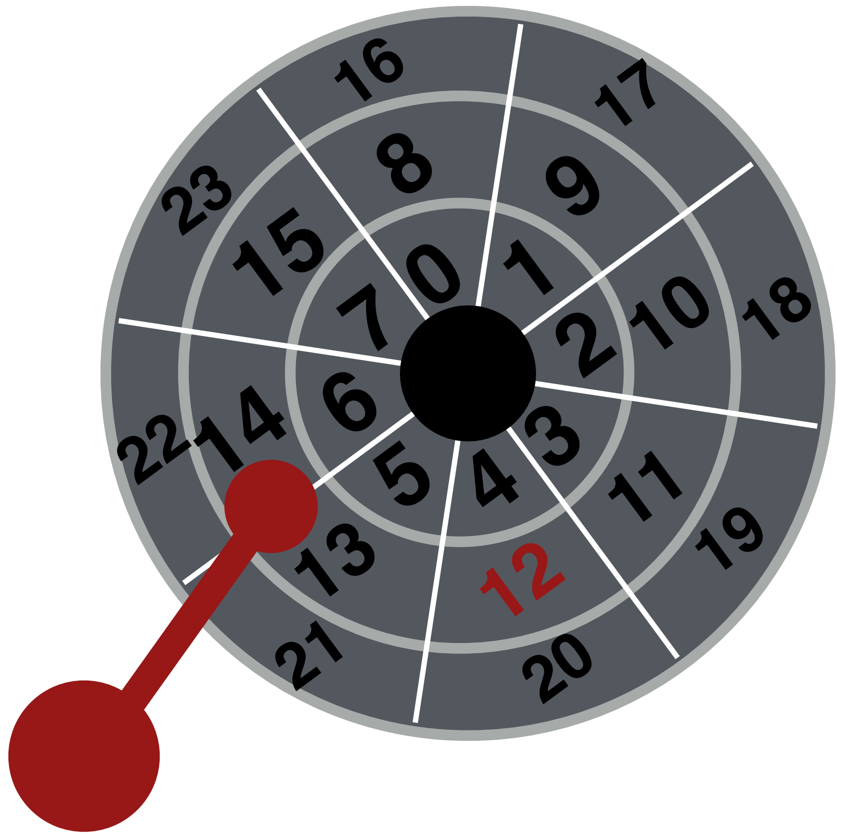
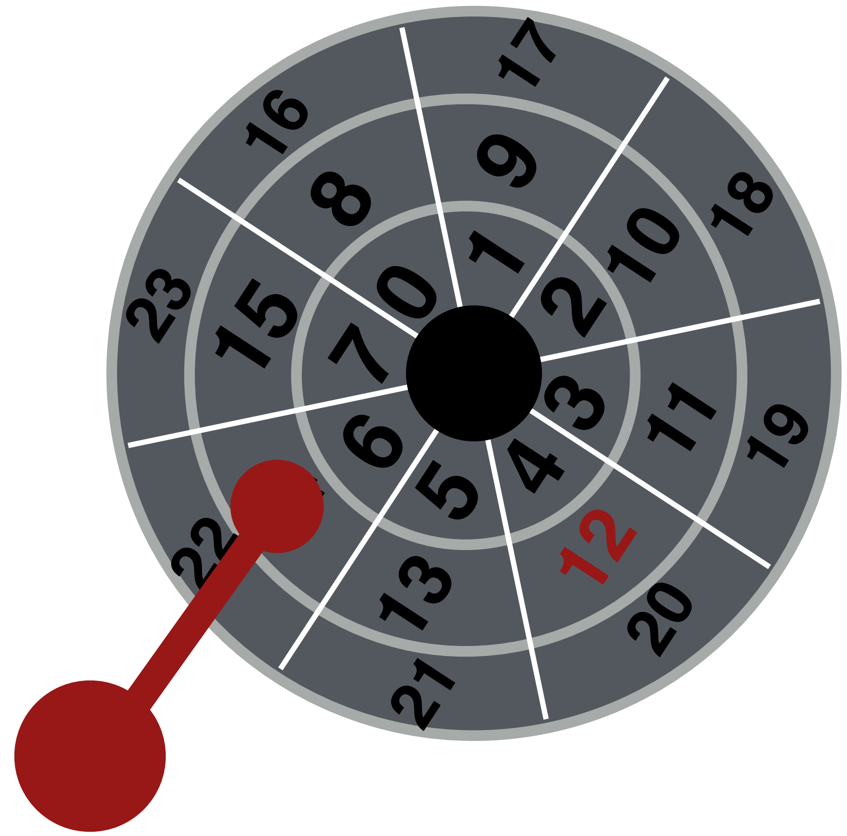


Wait for rotation.



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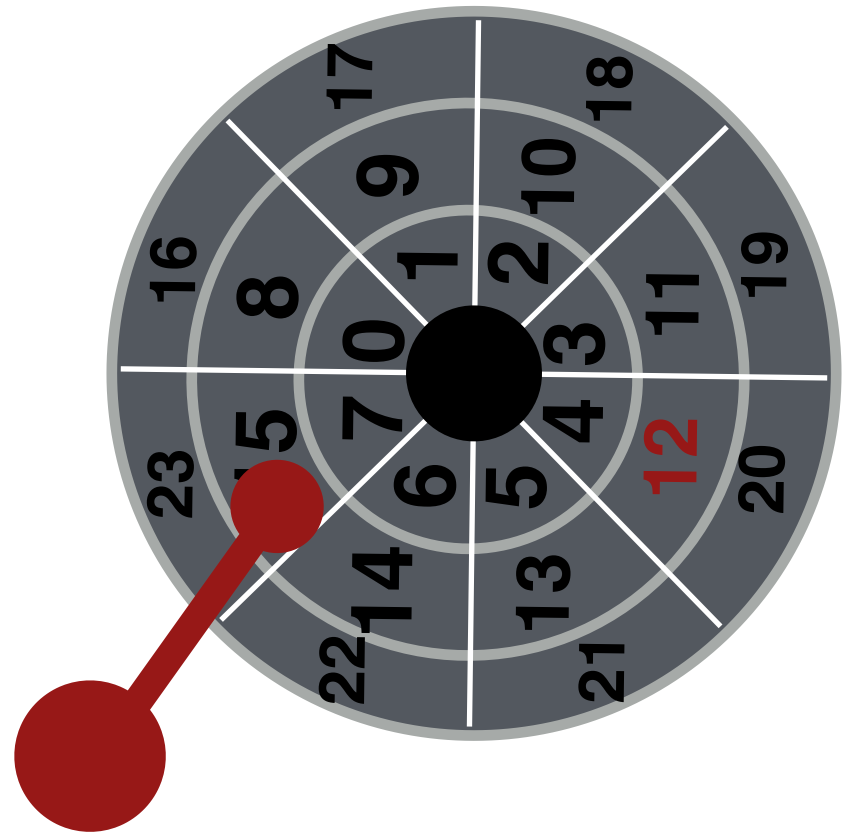

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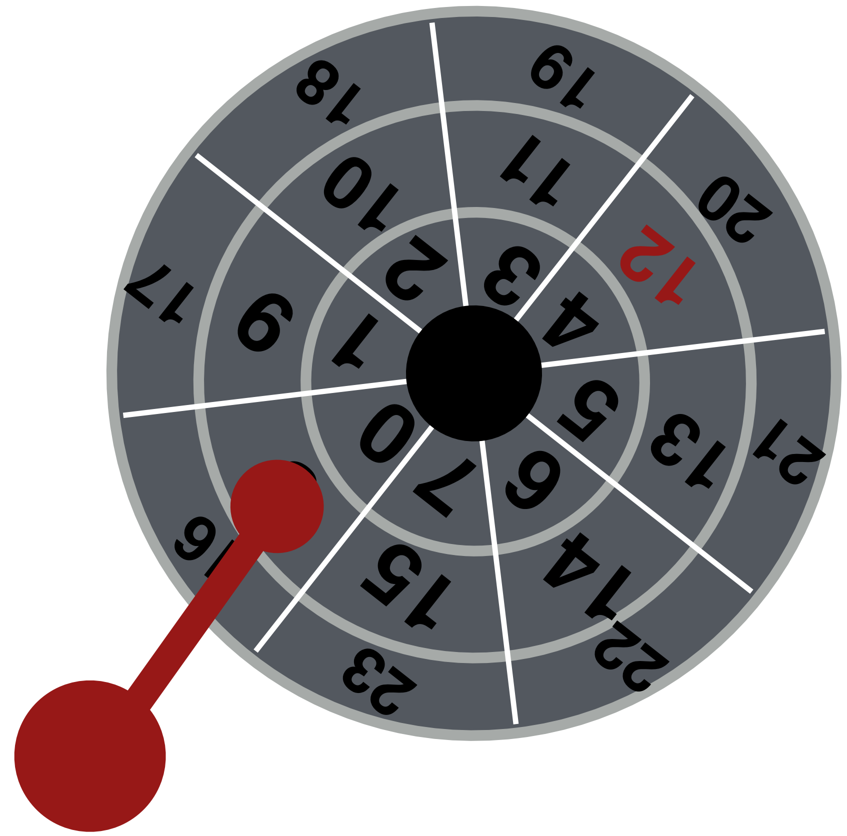

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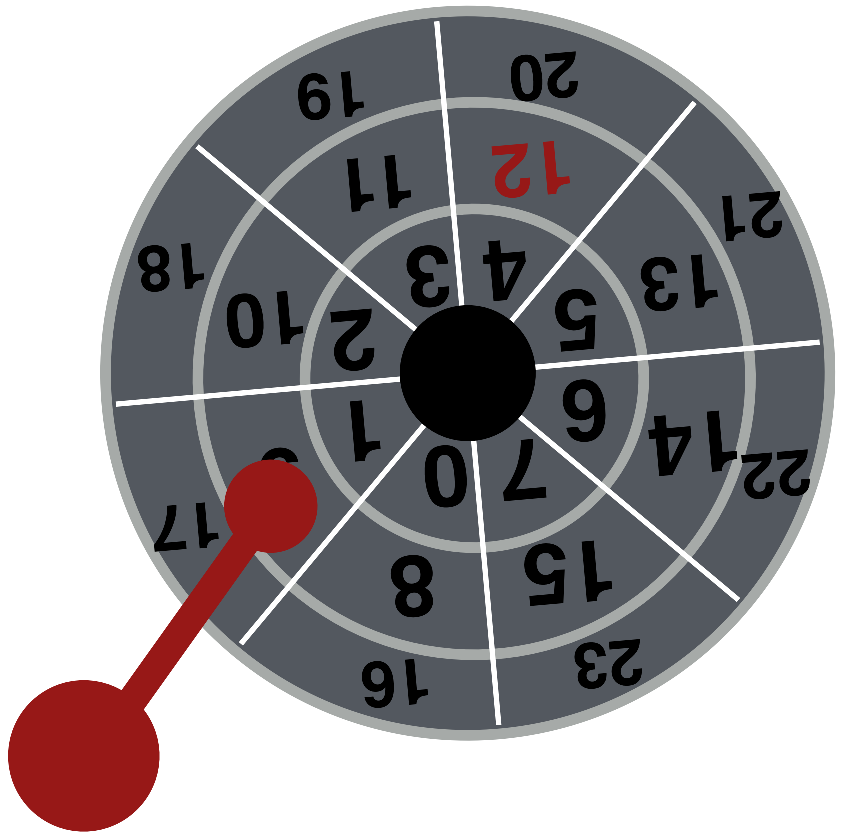

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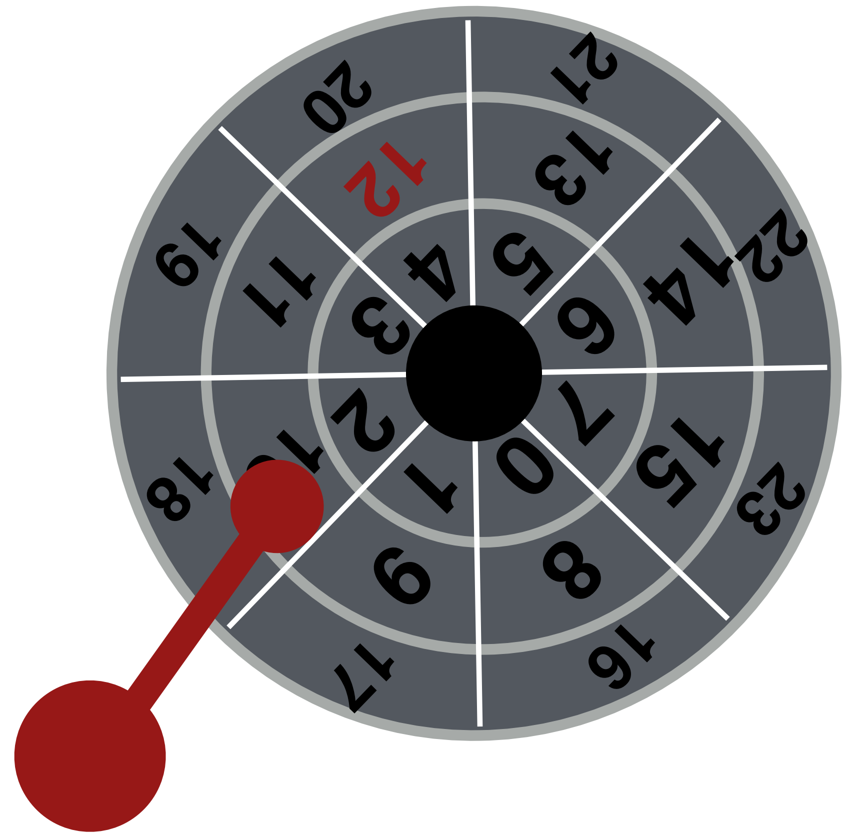

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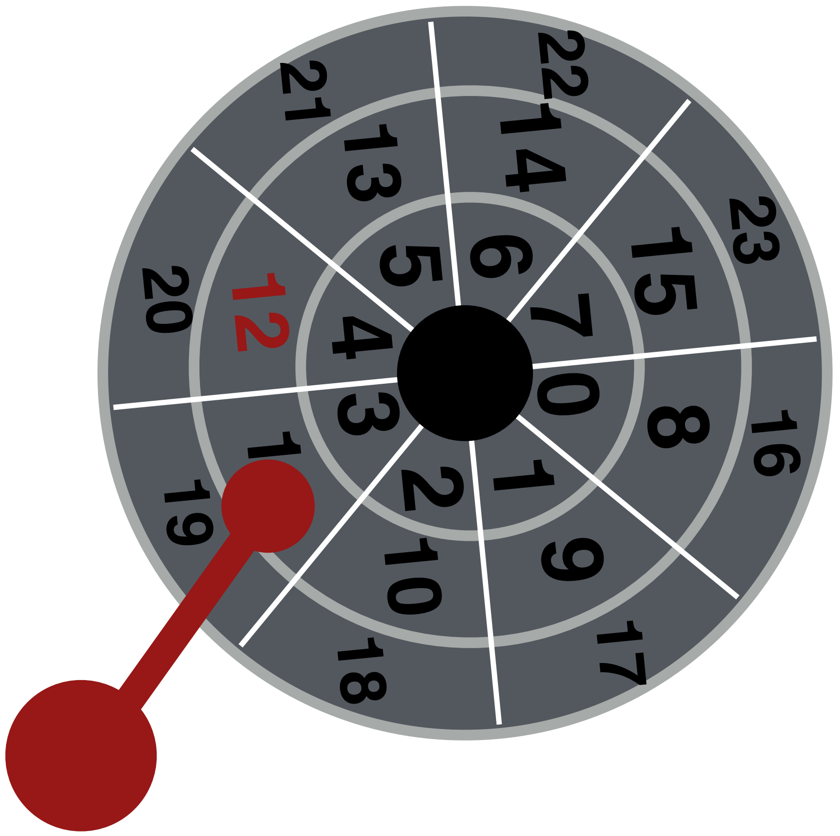
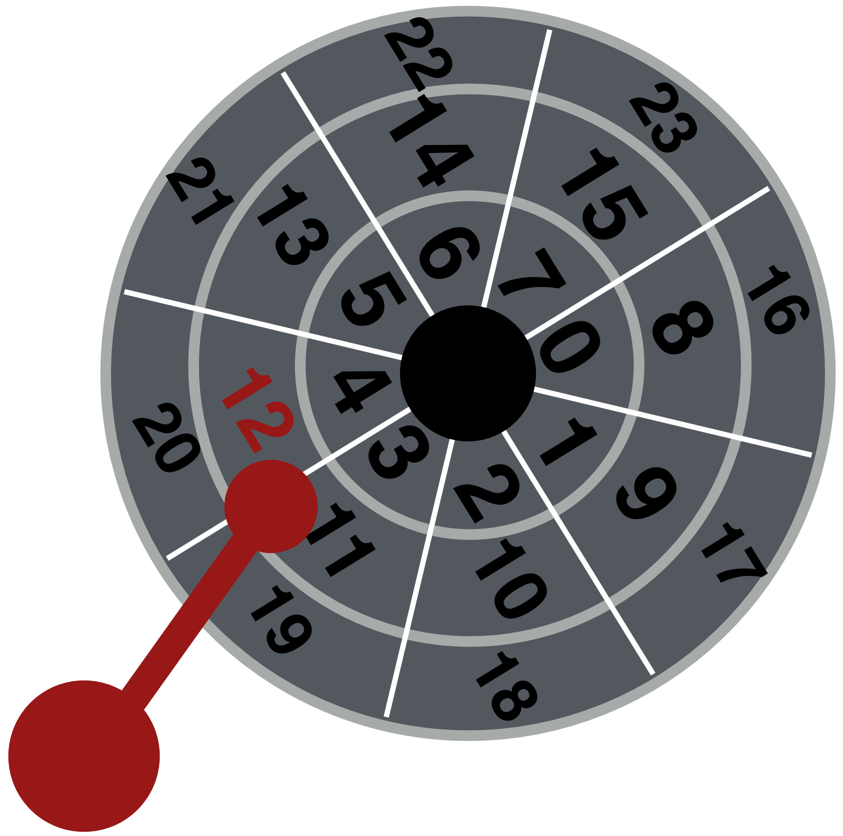


Transfer data.



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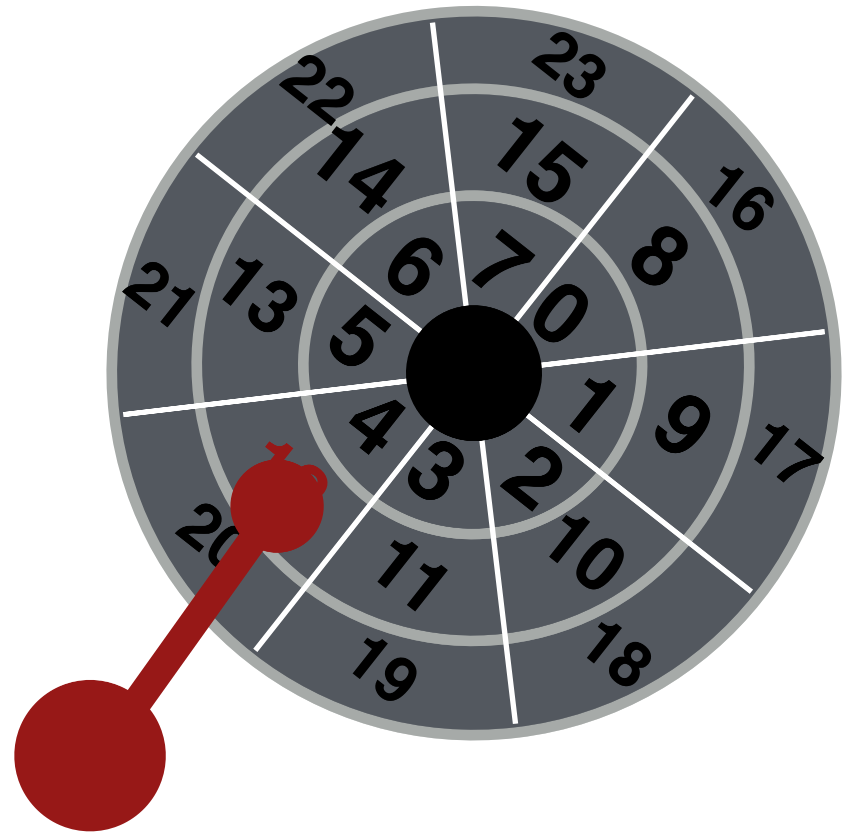

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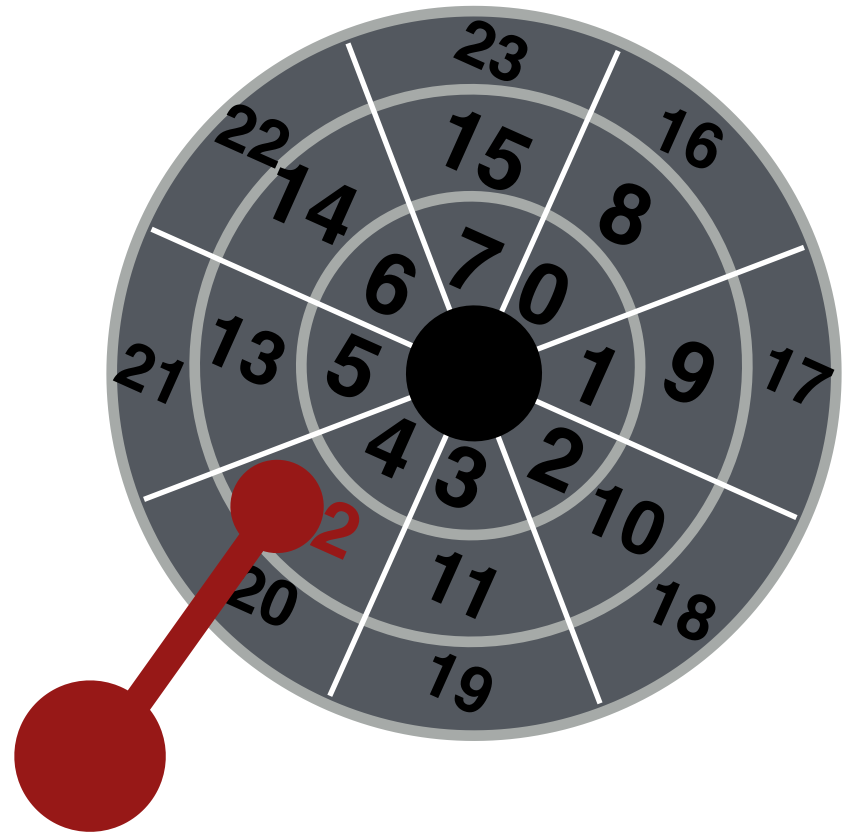
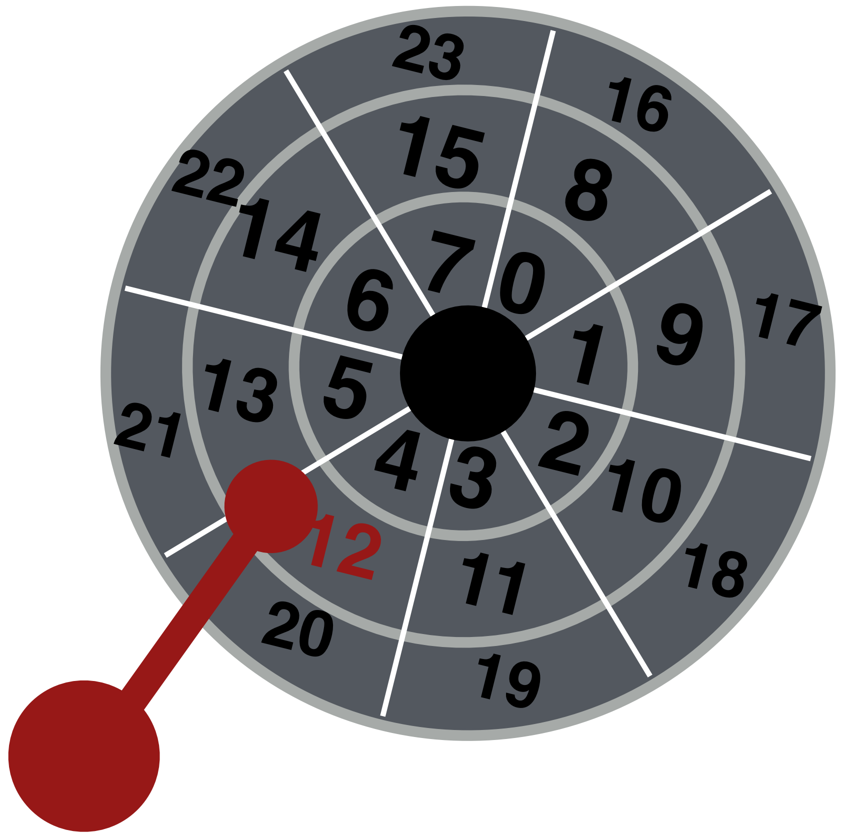


Yay!



Seek, Rotate, Transfer

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Entire seek often takes 4 - 10 ms.

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1 second / 120 rotations =

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1 / 7200 RPM =
1 minute / 7200 rotations =
1 second / 120 rotations =
12 ms / rotation

Seek, Rotate, Transfer

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- 7200 RPM is common, 15000 RPM is high end.

1 / 7200 RPM =
1 minute / 7200 rotations =
1 second / 120 rotations =
12 ms / rotation

so it may take **6 ms** on avg to rotate to target (0.5 * 12 ms)

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1s / 100 MB = 10 ms / MB = 4.9 us / sector
(assuming 512-byte sector)

Workload

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What kind of workload is fastest for disks?

Sequential: access sectors in order (transfer dominated)

Random: access sectors arbitrarily (seek+rotation dominated)

Demos: example-rand.csh and example-seq.csh

Disk Spec

	Cheetah	Barracuda
Capacity	300 GB	1 TB
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s
Platters	4	4
Cache	16 MB	32 MB

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Sequential workload: what is throughput for each?

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Cheeta: 125 MB/s.
Barracuda: 105 MB/s.

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Random workload: what is throughput for each?
(what else do you need to know?)

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Random workload: what is throughput for each?
Assume 16-KB reads.

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$$\text{avg rotation} = \frac{1}{2} \times \frac{1 \text{ min}}{15000}$$

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$$\text{avg rotation} = \frac{1}{2} \times \frac{1 \text{ min}}{15000} \times \frac{60 \text{ sec}}{1 \text{ min}} \times \frac{1000 \text{ ms}}{1 \text{ sec}} = 2 \text{ ms}$$

	Cheetah	Barracuda
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s

$$\text{transfer} = \frac{1 \text{ sec}}{125 \text{ MB}} \times 16 \text{ KB} \times \frac{1{,}000{,}000 \text{ us}}{1 \text{ sec}} = 125 \text{ us}$$

	Cheetah	Barracuda
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s

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Cheetah time = 4ms + 2ms + 125us = 6.1ms

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Cheetah time = 4ms + 2ms + 125us = 6.1ms

$$\text{throughput} = \frac{16\text{ KB}}{6.1\text{ms}} \times \frac{1\text{ MB}}{1024\text{ KB}} \times \frac{100\text{ ms}}{1\text{ sec}} = 2.5\text{ MB/s}$$

	Cheetah	Barracuda
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s

How long does an average 16-KB read take w/ Barracuda?

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Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s

How long does an average 16-KB read take w/ Barracuda?

$$\text{avg rotation} = \frac{1}{2} \times \frac{1\text{ min}}{7200} \times \frac{60\text{ sec}}{1\text{ min}} \times \frac{1000\text{ ms}}{1\text{ sec}} = 4.1\text{ ms}$$

	Cheetah	Barracuda
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s

How long does an average 16-KB read take w/ Barracuda?

$$\text{transfer} = \frac{1 \text{ sec}}{105 \text{ MB}} \times 16 \text{ KB} \times \frac{1{,}000{,}000 \text{ us}}{1 \text{ sec}} = 149 \text{ us}$$

	Cheetah	Barracuda
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s

How long does an average 16-KB read take w/ Barracuda?

Barracuda time = 9ms + 4.1ms + 149us = 13.2ms

$$\text{throughput} = \frac{16\ \text{KB}}{13.2\text{ms}} \times \frac{1\ \text{MB}}{1024\ \text{KB}} \times \frac{1000\ \text{ms}}{1\ \text{sec}}$$

	Cheetah	Barracuda
RPM	15,000	7,200
Avg Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s

How long does an average 16-KB read take w/ Barracuda?

Barracuda time = 9ms + 4.1ms + 149us = 13.2ms

$$\text{throughput} = \frac{16\text{ KB}}{13.2\text{ms}} \times \frac{1\text{ MB}}{1024\text{ KB}} \times \frac{1000\text{ ms}}{1\text{ sec}} = 1.2\text{ MB/s}$$