Hash Tables: Distributed Hash Tables

Michael Levin

Higher School of Economics

Data Structures
Data Structures and Algorithms

Outline

- Have you ever wondered, how large files are sometimes uploaded instantly to Dropbox?

- Have you ever wondered, how large files are sometimes uploaded instantly to Dropbox?
- Want to know how Dropbox, Google Drive and Yandex Disk save petabytes of storage using the ideas from this module?

- Have you ever wondered, how large files are sometimes uploaded instantly to Dropbox?
- Want to know how Dropbox, Google Drive and Yandex Disk save petabytes of storage using the ideas from this module?
- Interested in distributed storage?

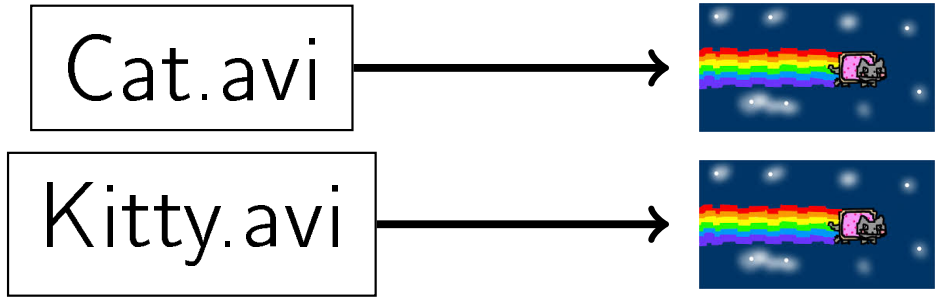
- Have you ever wondered, how large files are sometimes uploaded instantly to Dropbox?
- Want to know how Dropbox, Google Drive and Yandex Disk save petabytes of storage using the ideas from this module?
- Interested in distributed storage?
- This lesson

Storage optimization

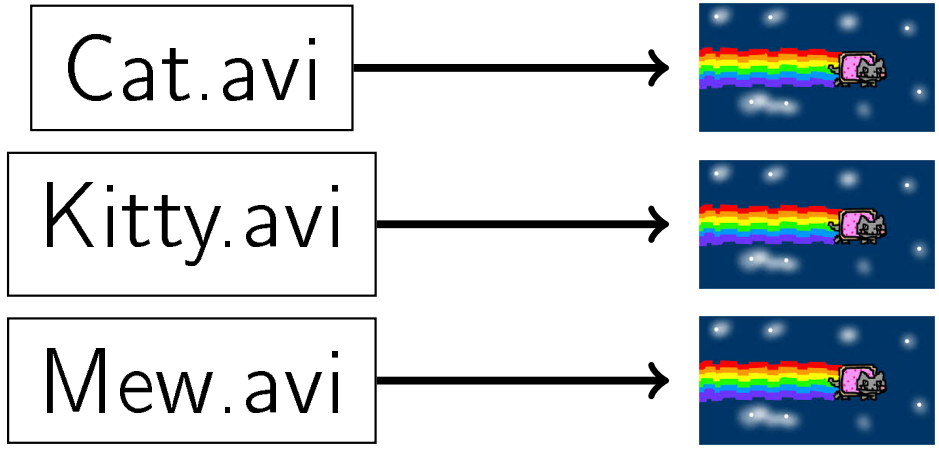
Storage optimization

Cat.avi

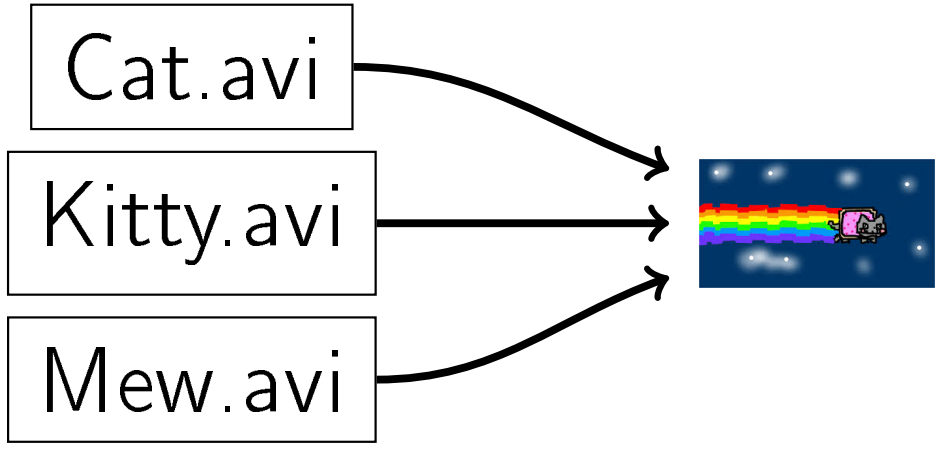
Storage optimization



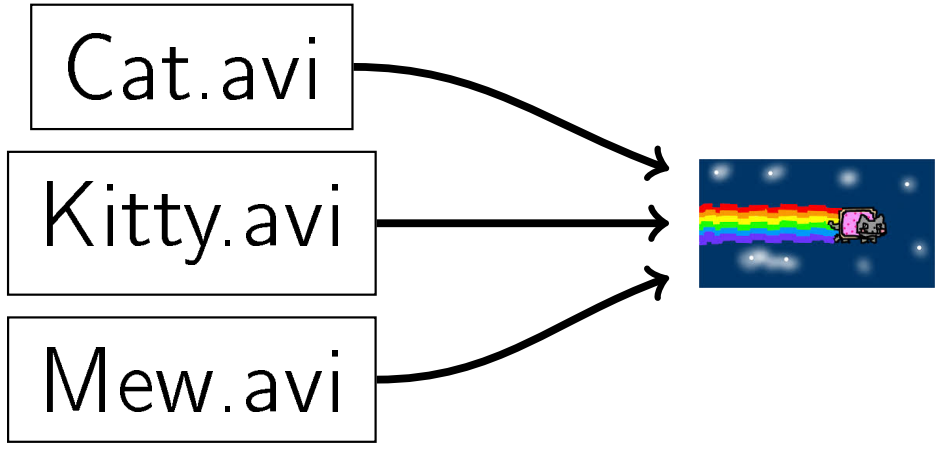
Storage optimization



Storage optimization

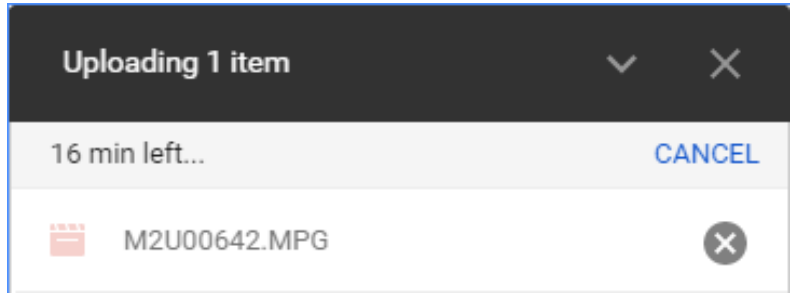


Storage optimization



66% of storage space saved!

New File Upload



- Need to determine whether there is already the same file in the system

Naive Comparison

- Upload new file

Naive Comparison

- Upload new file
- Go through all stored files

Naive Comparison

- Upload new file
- Go through all stored files
- Compare each stored file with new file byte-by-byte

Naive Comparison

- Upload new file
- Go through all stored files
- Compare each stored file with new file byte-by-byte
- If there's the same file, store a link to it instead of the new file

Drawbacks of Naive Comparison

- Have to upload the file first anyway

Drawbacks of Naive Comparison

- Have to upload the file first anyway
- $O(NS)$ to compare file of size S with N other files

Drawbacks of Naive Comparison

- Have to upload the file first anyway
- $O(NS)$ to compare file of size S with N other files
- N grows, so total running time of uploads grows as $O(N^2)$

Idea: Compare Hashes

- As in Rabin-Karp's algorithm, compare hashes of files first

Idea: Compare Hashes

- As in Rabin-Karp's algorithm, compare hashes of files first
- If hashes are different, files are different

Idea: Compare Hashes

- As in Rabin-Karp's algorithm, compare hashes of files first
- If hashes are different, files are different
- If there's a file with the same hash, upload and compare directly

Drawbacks of Hash Comparison

- There can be collisions

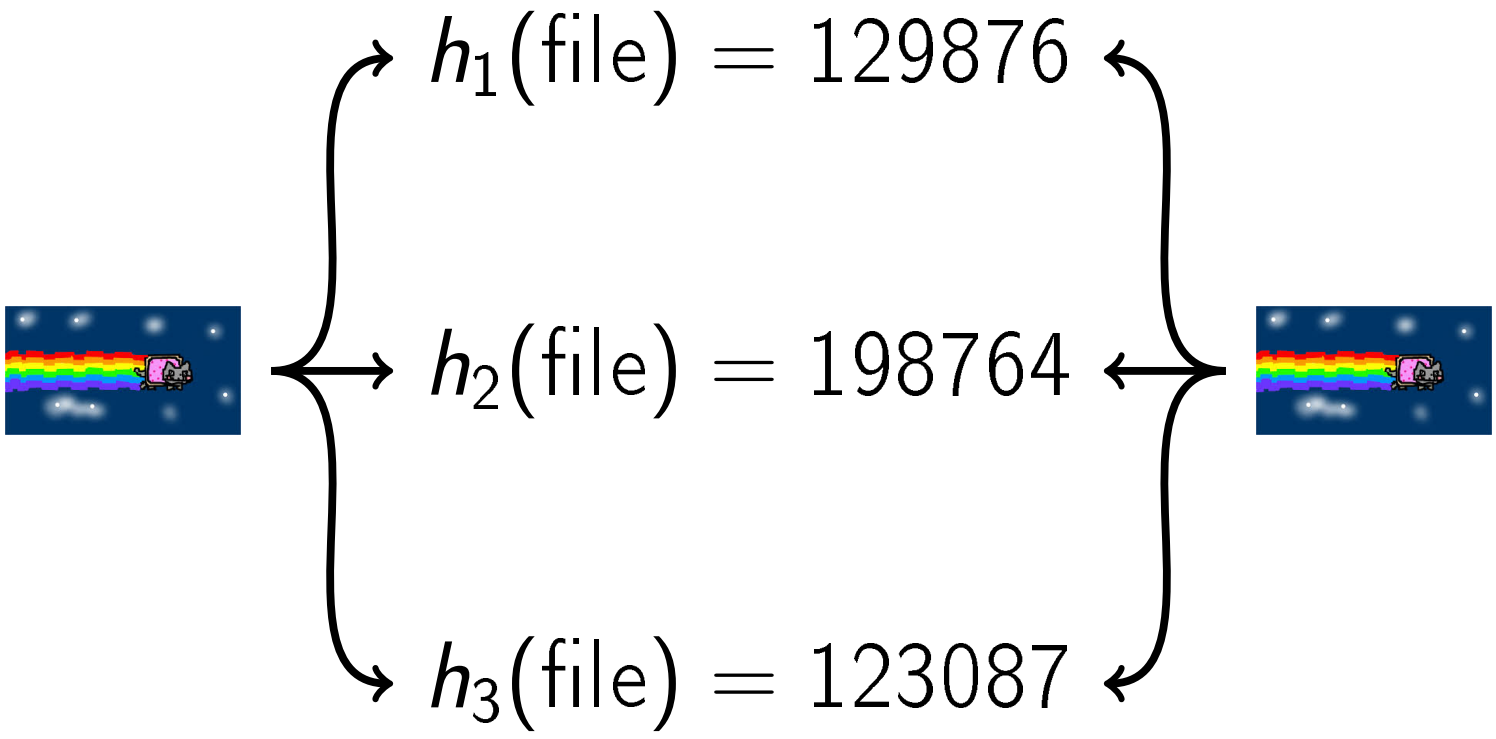
Drawbacks of Hash Comparison

- There can be collisions
- Still have to upload the file to compare directly

Drawbacks of Hash Comparison

- There can be collisions
- Still have to upload the file to compare directly
- Still have to compare with all N stored files

Idea: Several Hashes



Idea: Several Hashes

- Choose several different hash functions

Idea: Several Hashes

- Choose several different hash functions
- Polynomial hashing with different p or x

Idea: Several Hashes

- Choose several different hash functions
- Polynomial hashing with different p or x
- Compute all hashes for each file

Idea: Several Hashes

- Choose several different hash functions
- Polynomial hashing with different p or x
- Compute all hashes for each file
- If there's a file with all the same hashes, files are probably equal

Idea: Several Hashes

- Choose several different hash functions
- Polynomial hashing with different p or x
- Compute all hashes for each file
- If there's a file with all the same hashes, files are probably equal
- Don't upload the new file in this case!

Idea: Several Hashes

- Choose several different hash functions
- Polynomial hashing with different p or x
- Compute all hashes for each file
- If there's a file with all the same hashes, files are probably equal
- Don't upload the new file in this case!
- Compute hashes locally before upload

Problem: Collisions

- Collisions can happen even for several hashes simultaneously

Problem: Collisions

- Collisions can happen even for several hashes simultaneously
- There are algorithms to find collisions for known hash functions

Problem: Collisions

- Collisions can happen even for several hashes simultaneously
- There are algorithms to find collisions for known hash functions
- However, even for one hash function collisions are extremely rare

Problem: Collisions

- Collisions can happen even for several hashes simultaneously
- There are algorithms to find collisions for known hash functions
- However, even for one hash function collisions are extremely rare
- Using 3 or 5 hashes, you probably won't see a collision in a lifetime

Problem: $O(N)$ Comparisons

- Still have to compare with N already stored files

Idea:Precompute Hashes

- When a file is submitted for upload, hashes are computed anyway

Idea:Precompute Hashes

- When a file is submitted for upload, hashes are computed anyway
- Store file addresses in a hash table

Idea:Precompute Hashes

- When a file is submitted for upload, hashes are computed anyway
- Store file addresses in a hash table
- Also store all the hashes there

Idea:Precompute Hashes

- When a file is submitted for upload, hashes are computed anyway
- Store file addresses in a hash table
- Also store all the hashes there
- Only need the hashes to search in the table

Final Solution

- Choose $3 - 5$ hash functions

Final Solution

- Choose $3 - 5$ hash functions
- Store file addresses and hashes in a hash table

Final Solution

- Choose $3 - 5$ hash functions
- Store file addresses and hashes in a hash table
- Compute the hashes of new file locally before upload

Final Solution

- Choose $3 - 5$ hash functions
- Store file addresses and hashes in a hash table
- Compute the hashes of new file locally before upload
- Search new file in the hash table

Final Solution

- Choose $3 - 5$ hash functions
- Store file addresses and hashes in a hash table
- Compute the hashes of new file locally before upload
- Search new file in the hash table
- Search is successful if all the hashes coincide

Final Solution

- Choose $3 - 5$ hash functions
- Store file addresses and hashes in a hash table
- Compute the hashes of new file locally before upload
- Search new file in the hash table
- Search is successful if all the hashes coincide
- Don't upload the file, store a link to the existing one

More Problems

- Billions of files are uploaded daily

More Problems

- Billions of files are uploaded daily
- Trillions stored already

More Problems

- Billions of files are uploaded daily
- Trillions stored already
- Too big for a simple hash table

More Problems

- Billions of files are uploaded daily
- Trillions stored already
- Too big for a simple hash table
- Millions of users upload simultaneously

More Problems

- Billions of files are uploaded daily
- Trillions stored already
- Too big for a simple hash table
- Millions of users upload simultaneously
- Too many requests for a single table

More Problems

- Billions of files are uploaded daily
- Trillions stored already
- Too big for a simple hash table
- Millions of users upload simultaneously
- Too many requests for a single table
- See the next lecture

Outline

Big Data

- Need to store trillions or more objects

Big Data

- Need to store trillions or more objects
- File addresses, user profiles, e-mails

Big Data

- Need to store trillions or more objects
- File addresses, user profiles, e-mails
- Need fast search/access

Big Data

- Need to store trillions or more objects
- File addresses, user profiles, e-mails
- Need fast search/access
- Hash tables provide $O(1)$ search/access on average, but for $n = 10^{12}$, $O(n + m)$ memory becomes too big

Big Data

- Need to store trillions or more objects
- File addresses, user profiles, e-mails
- Need fast search/access
- Hash tables provide $O(1)$ search/access on average, but for $n = 10^{12}$, $O(n + m)$ memory becomes too big
- Solution: distributed hash tables

Distributed Hash Table

- Get 1000 computers

Distributed Hash Table

- Get 1000 computers
- Create a hash table on each of them

Distributed Hash Table

- Get 1000 computers
- Create a hash table on each of them
- Determine which computer "owns" object O: number $h(O)$ mod 1000

Distributed Hash Table

- Get 1000 computers
- Create a hash table on each of them
- Determine which computer "owns" object O: number $h(O)$ mod 1000
- Send request to that computer, search/modify in the local hash table

Problems

- Computers sometimes break

Problems

- Computers sometimes break
- Computer breaks once in 2 years $\Rightarrow$ one of 1000 computers breaks every day!

Problems

- Computers sometimes break
- Computer breaks once in 2 years $\Rightarrow$ one of 1000 computers breaks every day!
- Store several copies of the data

Problems

- Computers sometimes break
- Computer breaks once in 2 years $\Rightarrow$ one of 1000 computers breaks every day!
- Store several copies of the data
- Need to relocate the data from the broken computer

Problems

- Computers sometimes break
- Computer breaks once in 2 years $\Rightarrow$ one of 1000 computers breaks every day!
- Store several copies of the data
- Need to relocate the data from the broken computer
- Service grows, and new computers are added to the cluster

Problems

- Computers sometimes break
- Computer breaks once in 2 years $\Rightarrow$ one of 1000 computers breaks every day!
- Store several copies of the data
- Need to relocate the data from the broken computer
- Service grows, and new computers are added to the cluster
- $h(O) \bmod 1000$ no longer works

Consistent Hashing

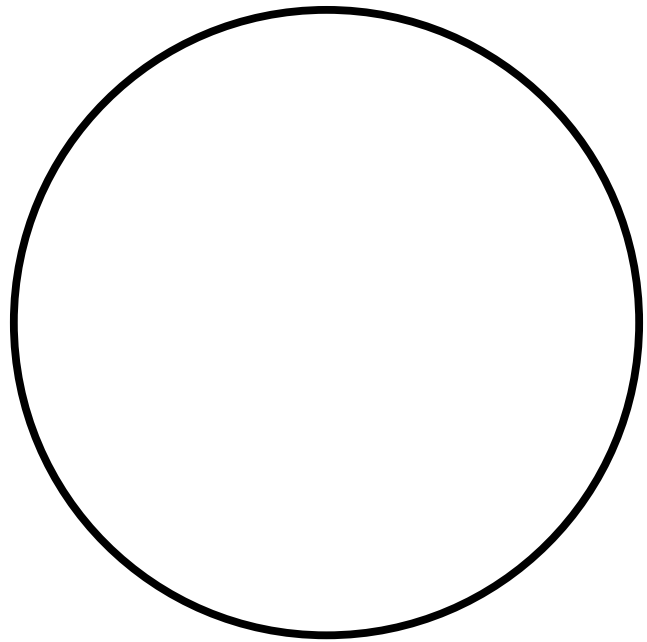
- Choose hash function h with cardinality m and put numbers from 0 to $m - 1$ on a circle clockwise

Consistent Hashing

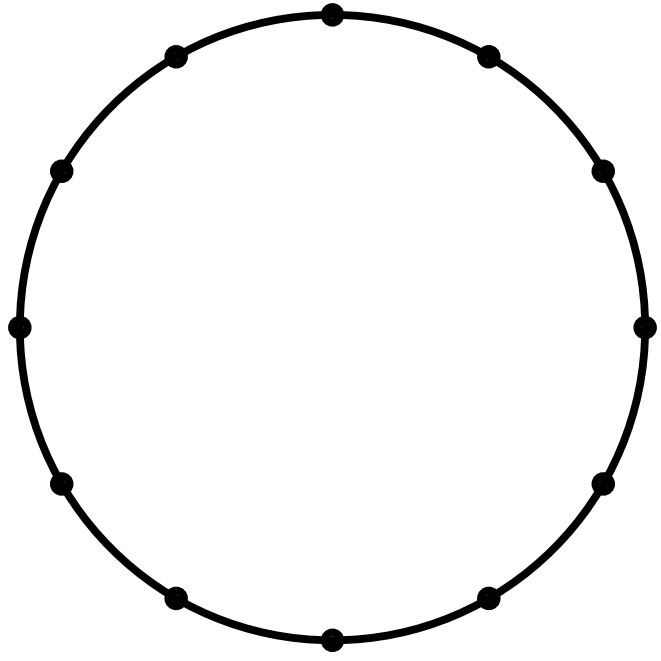
- Choose hash function h with cardinality m and put numbers from 0 to $m - 1$ on a circle clockwise
- Each object O is then mapped to a point on the circle with number $h(O)$

Consistent Hashing

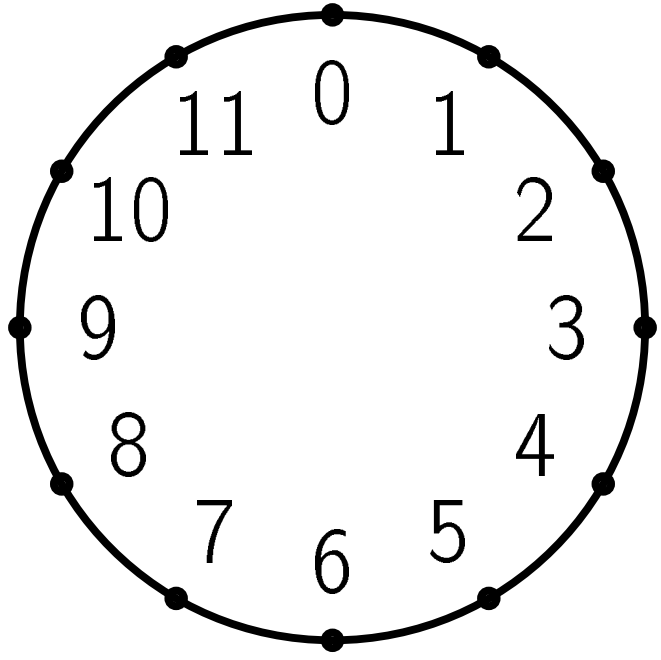
- Choose hash function h with cardinality m and put numbers from 0 to $m - 1$ on a circle clockwise
- Each object O is then mapped to a point on the circle with number $h(O)$
- Map computer IDs to the same circle: $compID \rightarrow$ point number $h(compID)$



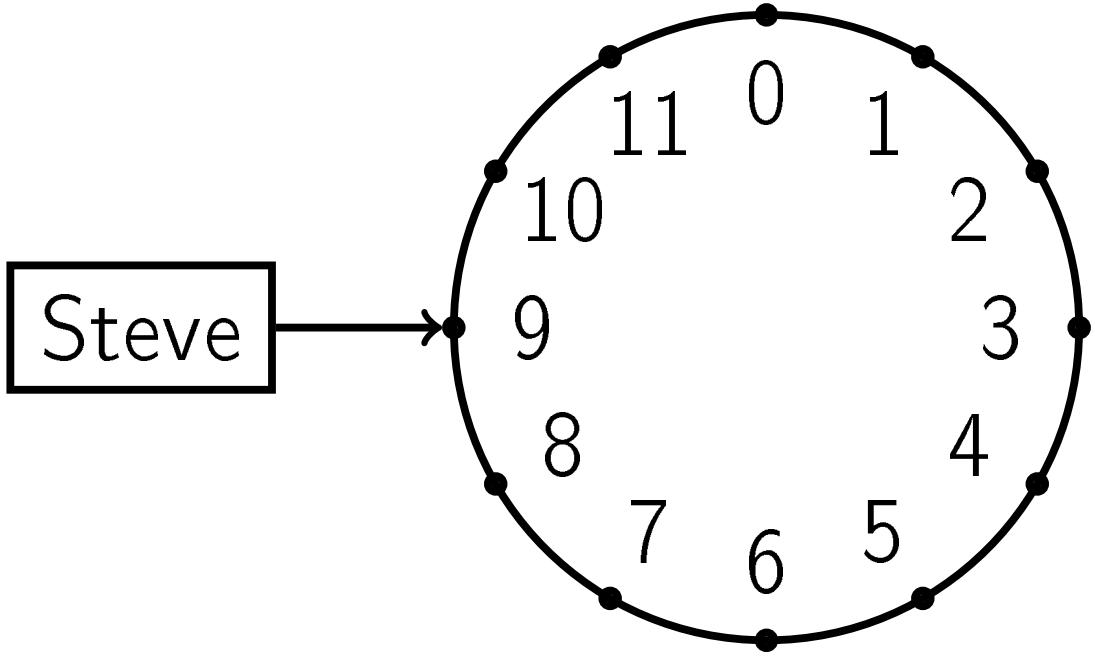
$m = 12$

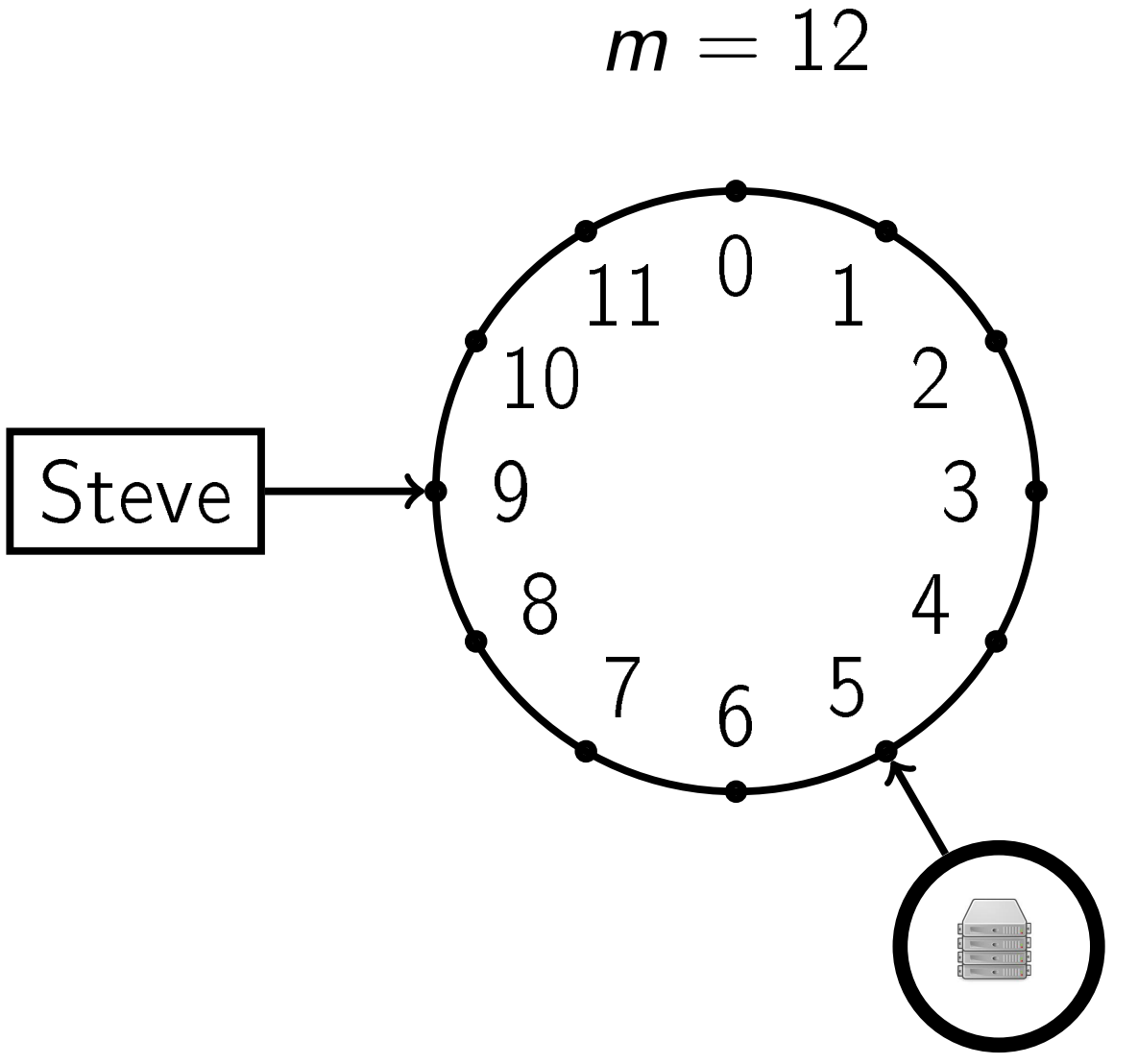


$m = 12$



$m = 12$



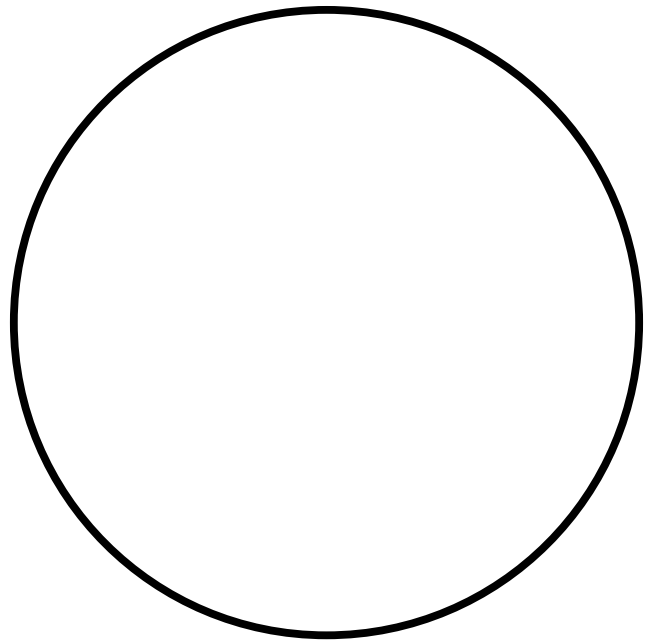

$m = 12$
0
1
2
3
4
5
6
7
8
9
10
11
Steve
ID=253

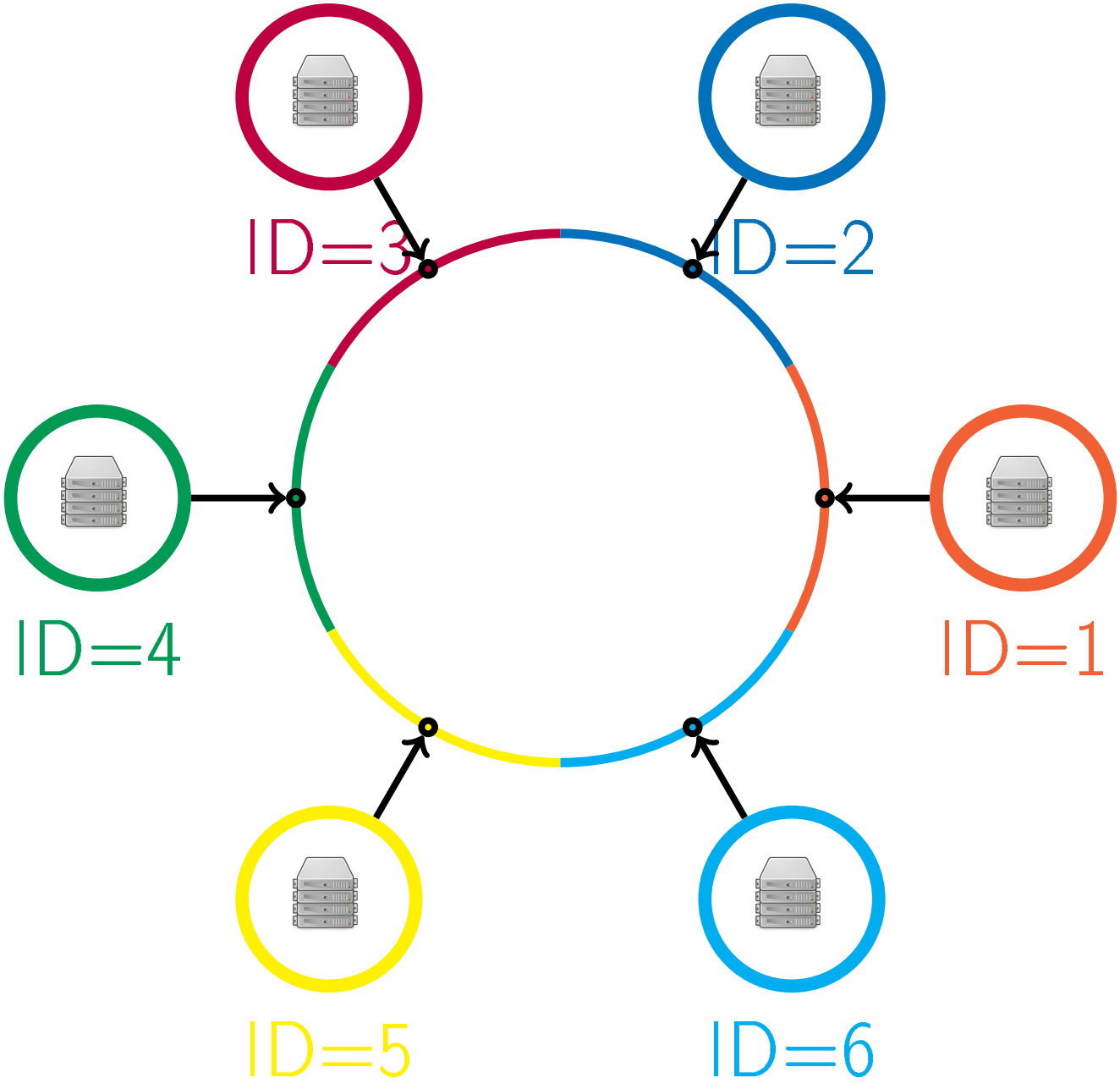
Consistent Hashing

- Each object is stored on the "closest" computer

Consistent Hashing

- Each object is stored on the "closest" computer
- Each computer stores all objects falling on some arc of the circle



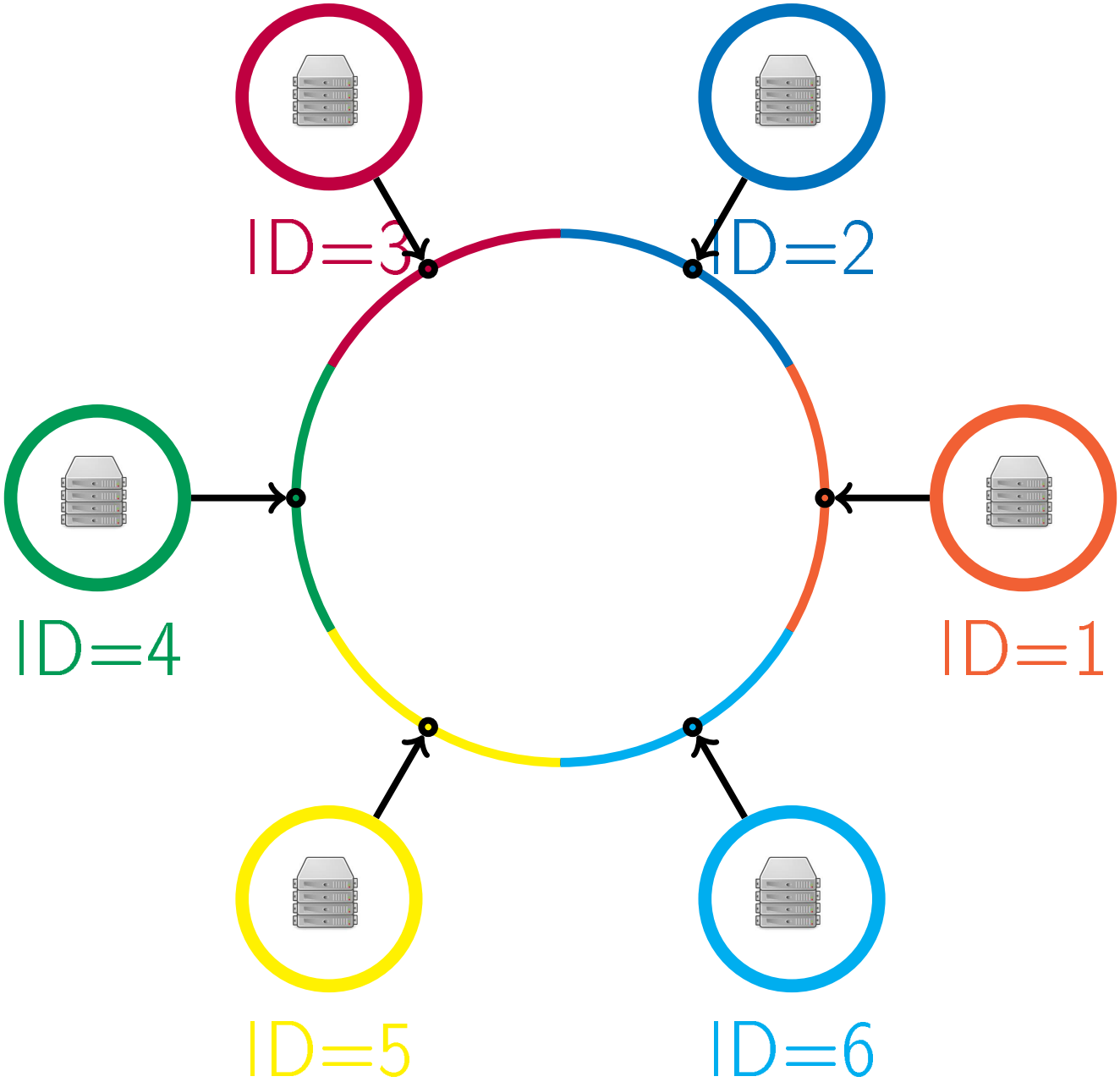

ID=3
ID=2
ID=4
ID=1
ID=5
ID=6

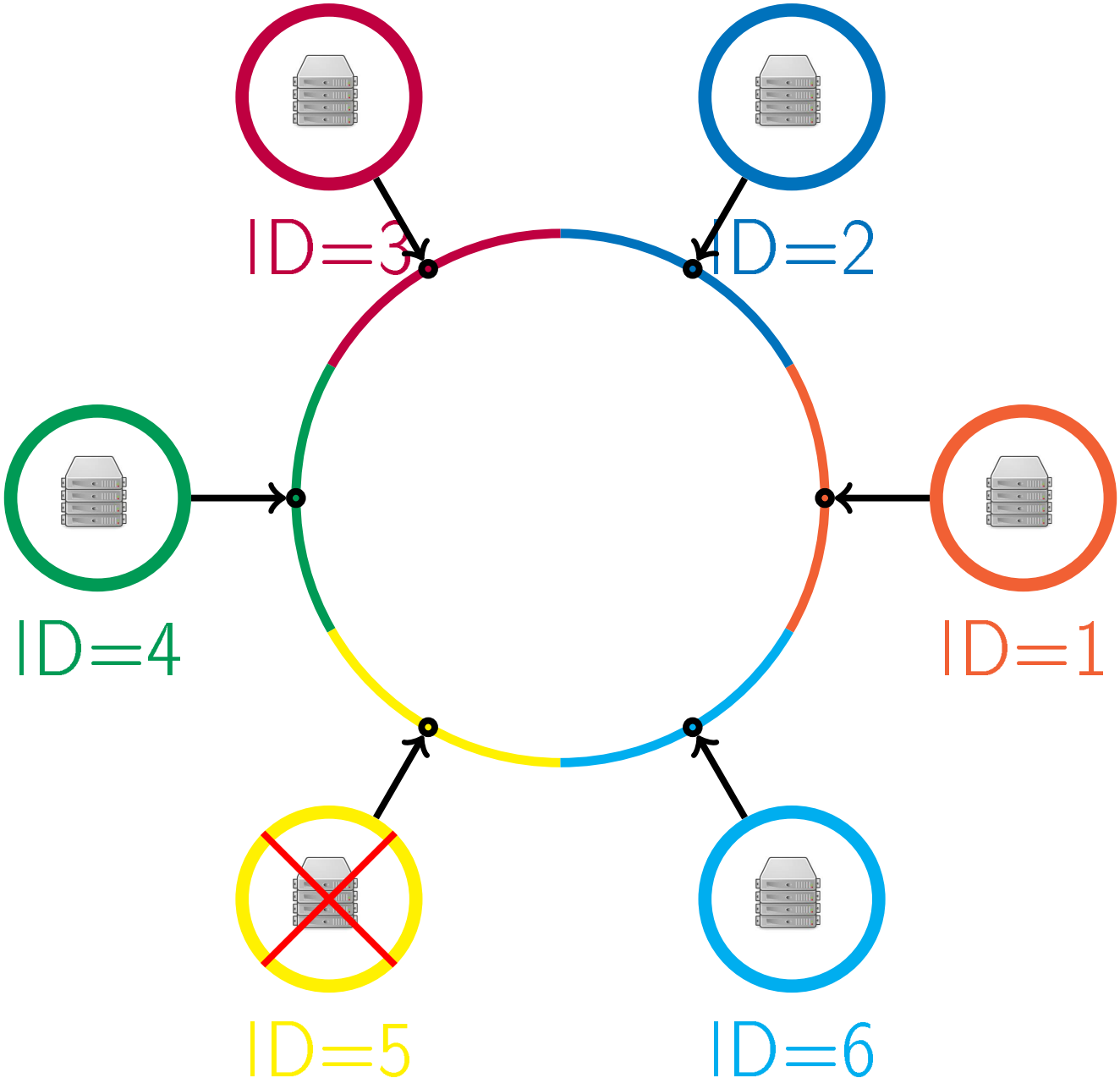
Computers In and Out

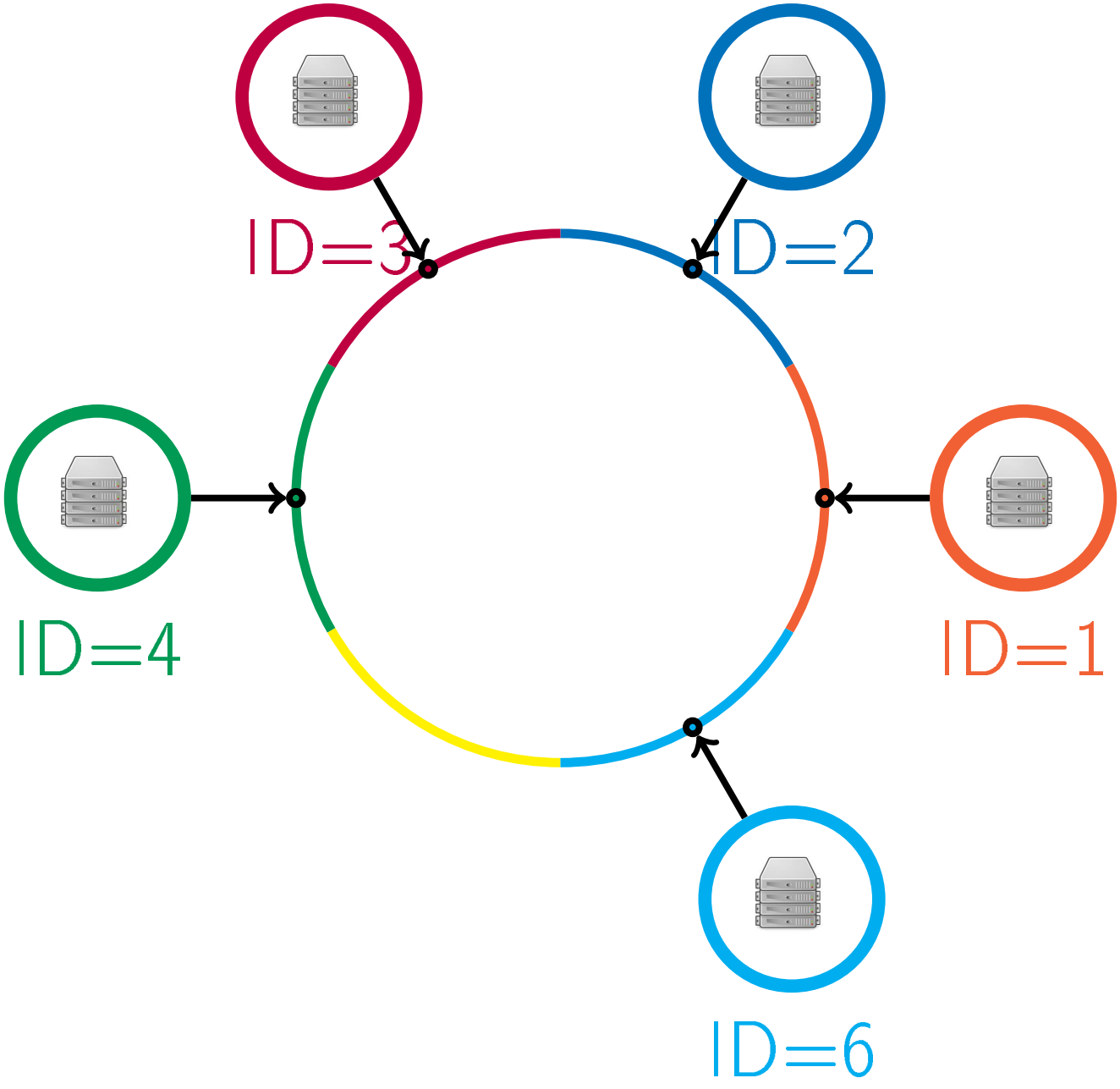
- When a computer goes off, “neighbors” take its data

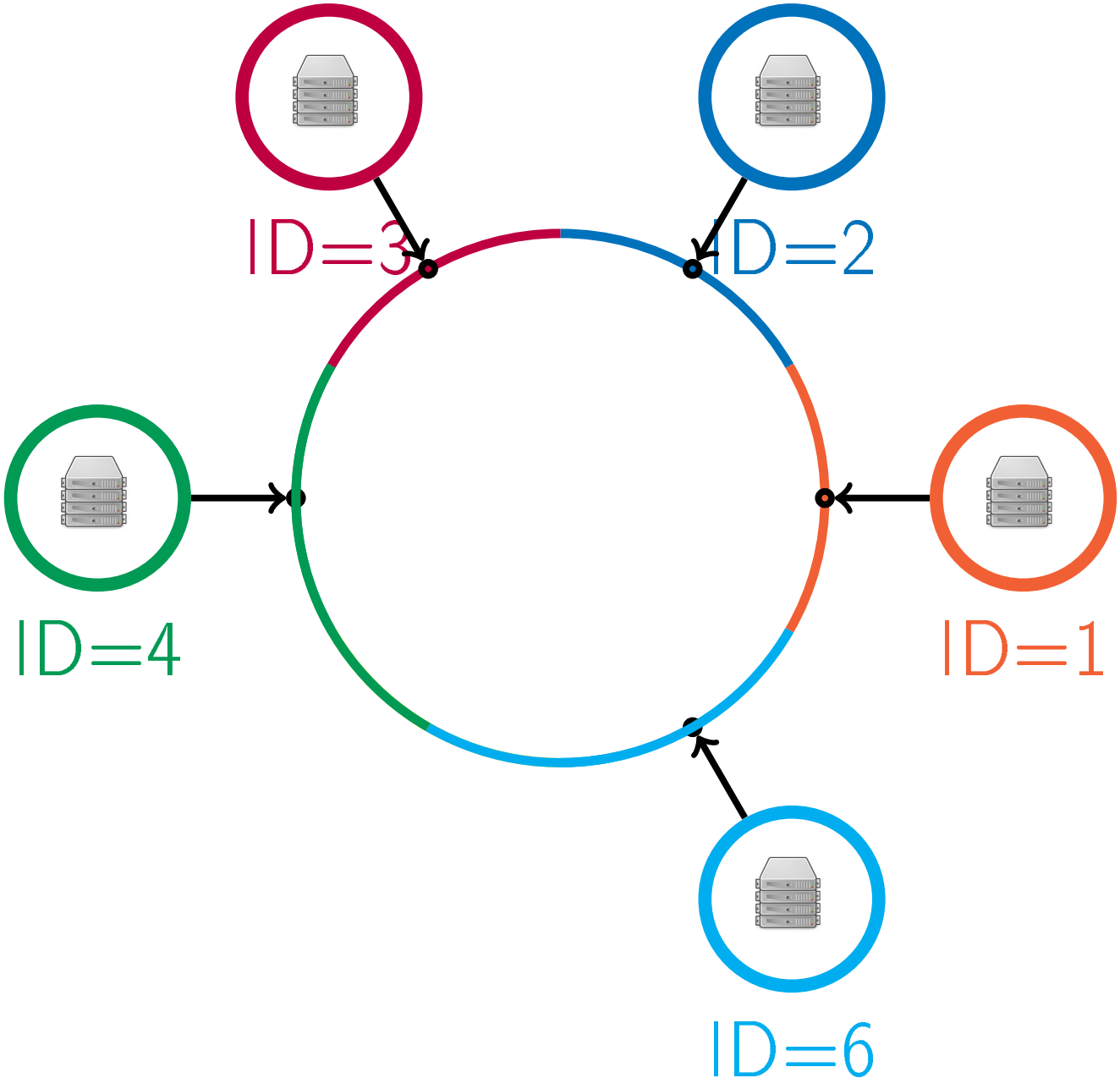
Computers In and Out

- When a computer goes off, "neighbors" take its data
- When a new computer is added, it takes data from the "neighbors"


ID=3
ID=2
ID=4
ID=1
ID=5
ID=6


ID=3
ID=2
ID=4
ID=1
ID=5
ID=6


ID=3
ID=2
ID=4
ID=1
ID=6


ID=3
ID=2
ID=4
ID=1
ID=6

Overlay Network

- Need to copy/relocate data

Overlay Network

- Need to copy/relocate data
- How will a node know where to send the data?

Overlay Network

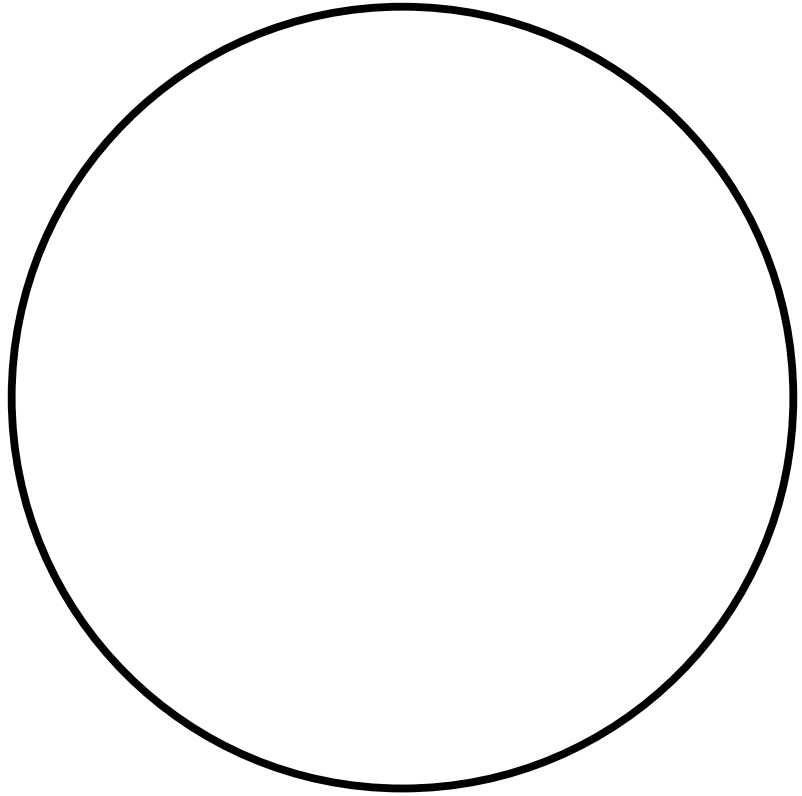
- Need to copy/relocate data
- How will a node know where to send the data?
- Each node will know a few neighbors

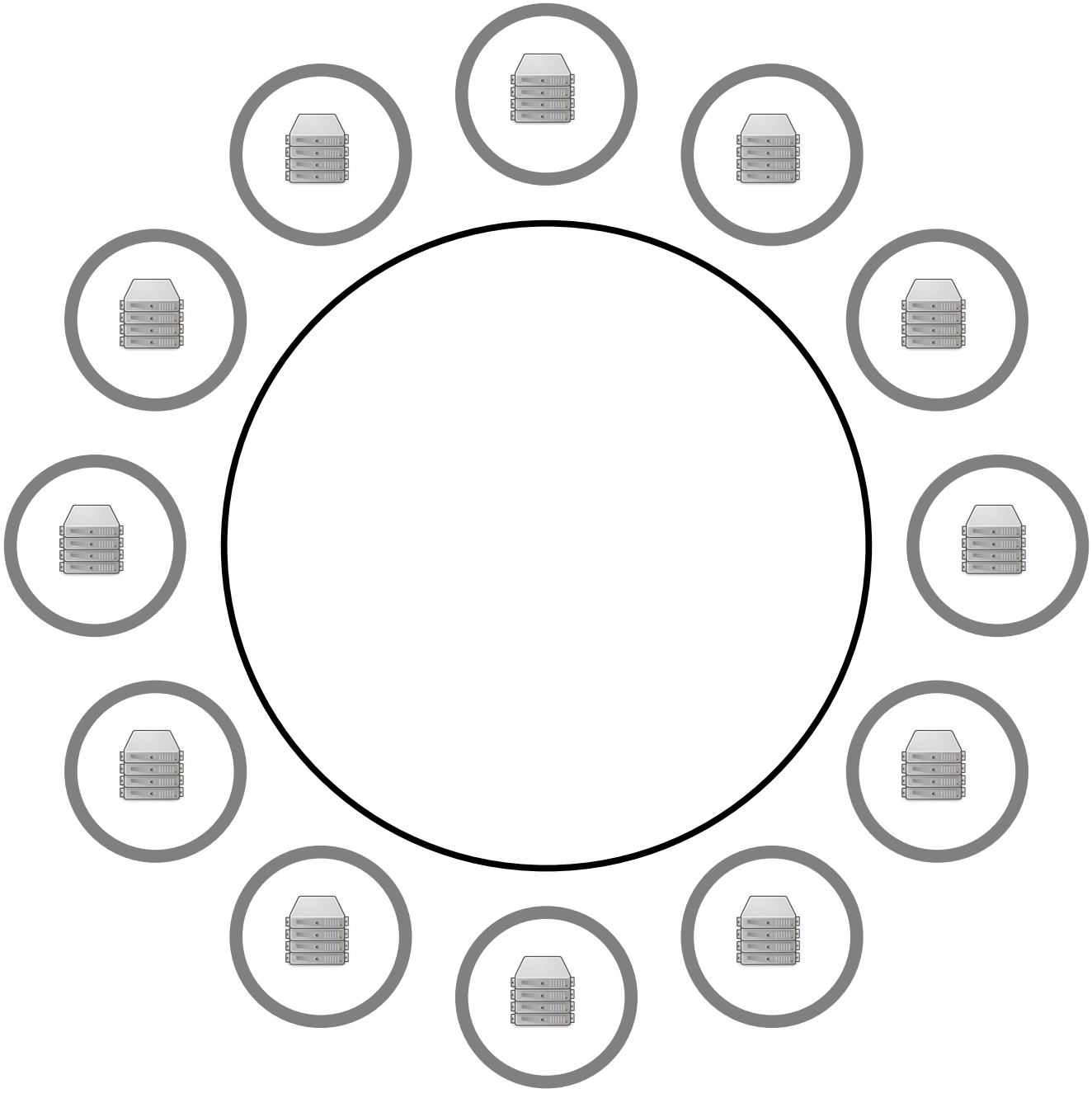
Overlay Network

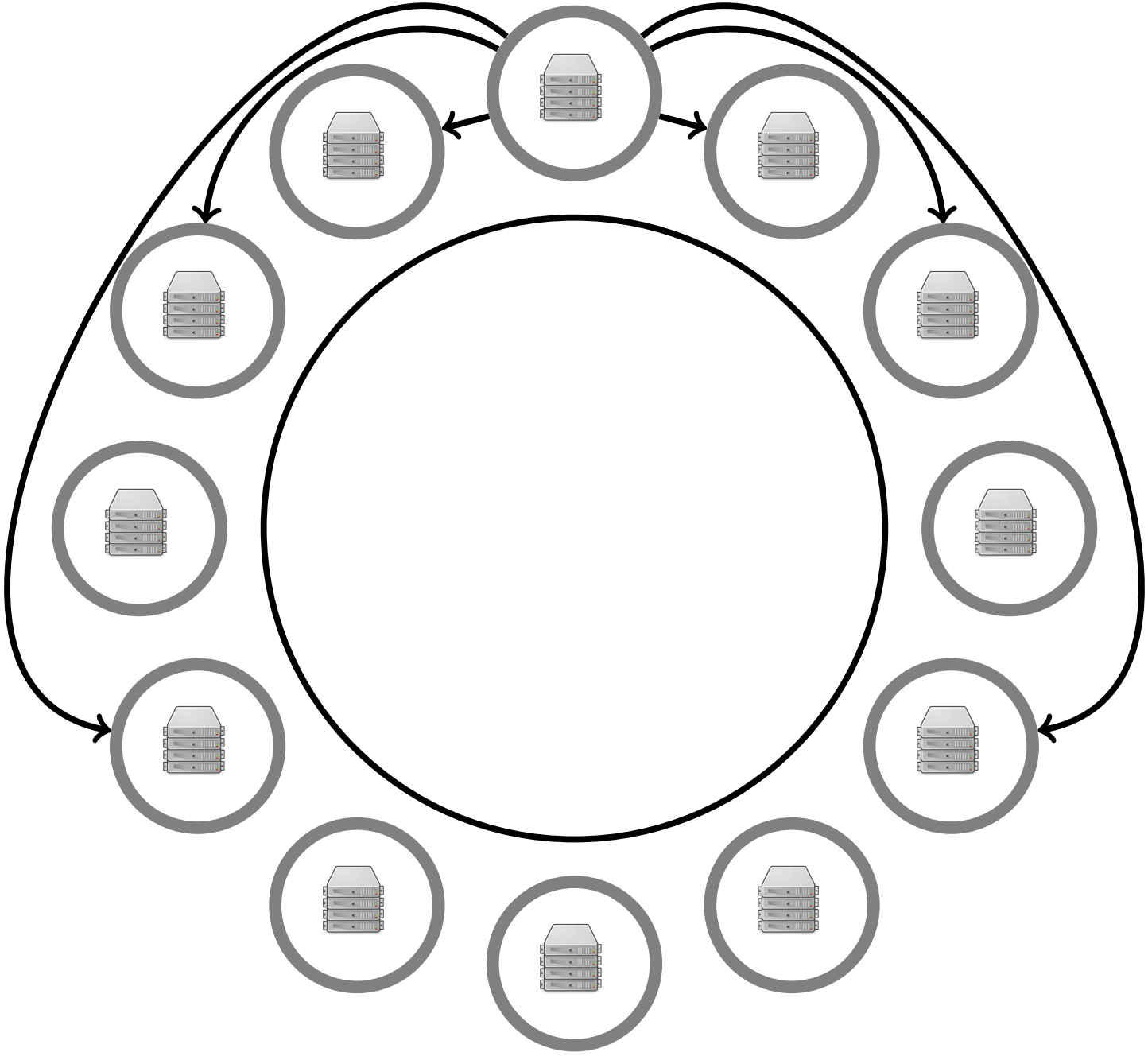
- Need to copy/relocate data
- How will a node know where to send the data?
- Each node will know a few neighbors
- For each key, each node will either store it or know some node "closer" to this key

Overlay Network

- Need to copy/relocate data
- How will a node know where to send the data?
- Each node will know a few neighbors
- For each key, each node will either store it or know some node "closer" to this key
- E.g., each node knows neighbors, $\pm 1, \pm 2, \pm 4, \pm 8, \ldots$ — $O(\log n)$ nodes, and can get/send any key in $O(\log n)$







Conclusion

- Distributed Hash Tables (DHT) store Big Data on many computers
- Consistent Hashing (CH) is one way to determine which computer stores which data
- CH uses mapping of keys and computer IDs on a circle
- Each computer stores a range of keys
- Overlay Network is used to route the data to/from the right computer