Decentralized Systems Engineering

CS-438 – Fall 2025

DEDIS

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EPFL

Credits: P. Tennage, C. Basescu, et al.

So far...

- Decentralized communication & search
- Focusing on (mostly) unstructured networks

Characteristics:

- (Nearly) stateless
- Simple to engineer
- Expressive search
- Optimizations require (true) random sampling (hard)
- ☹ inefficient, $O(\sqrt{n})$ search at best

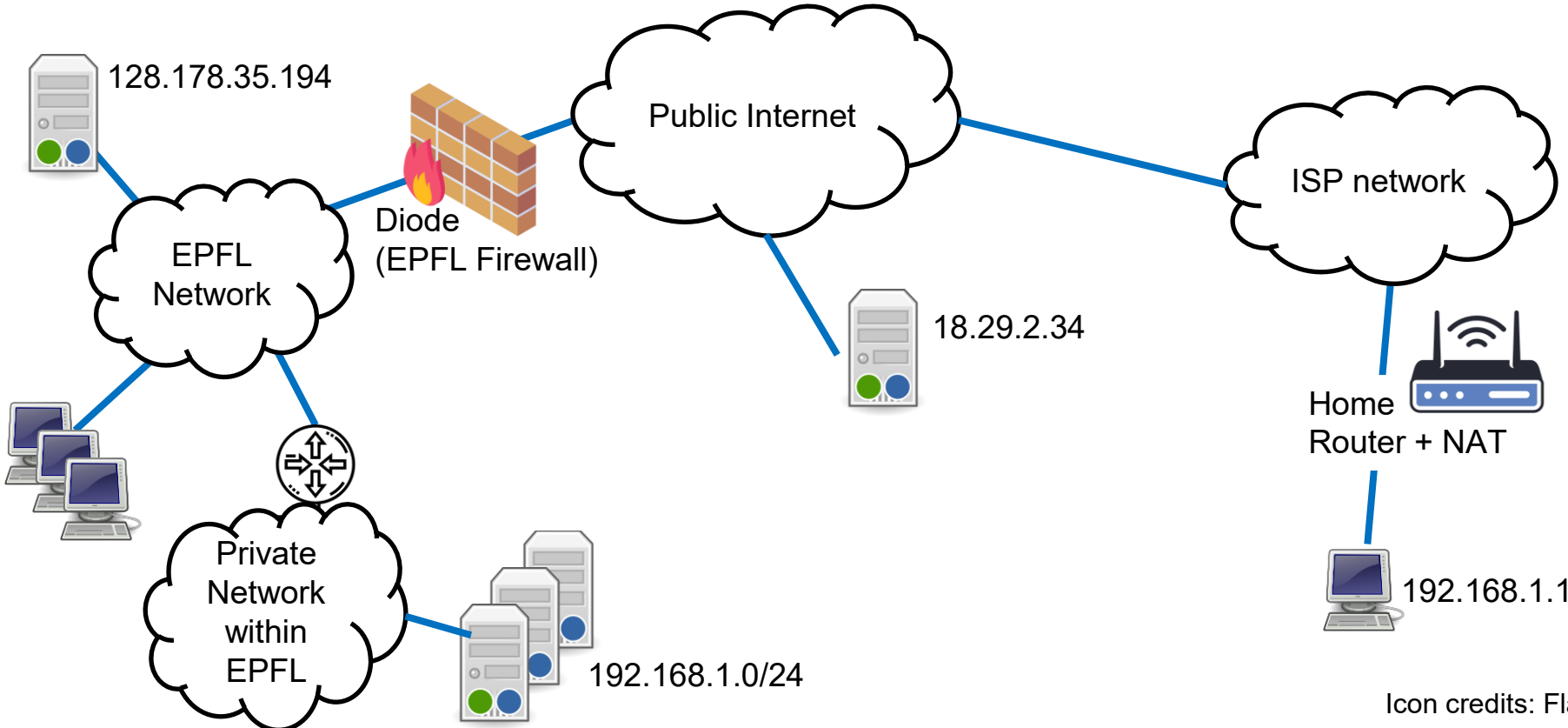
Can we aim for $O(\log n)$ efficiency ?
→ later today

Ad-hoc Routing Protocols

Finding your way through ad-hoc networks

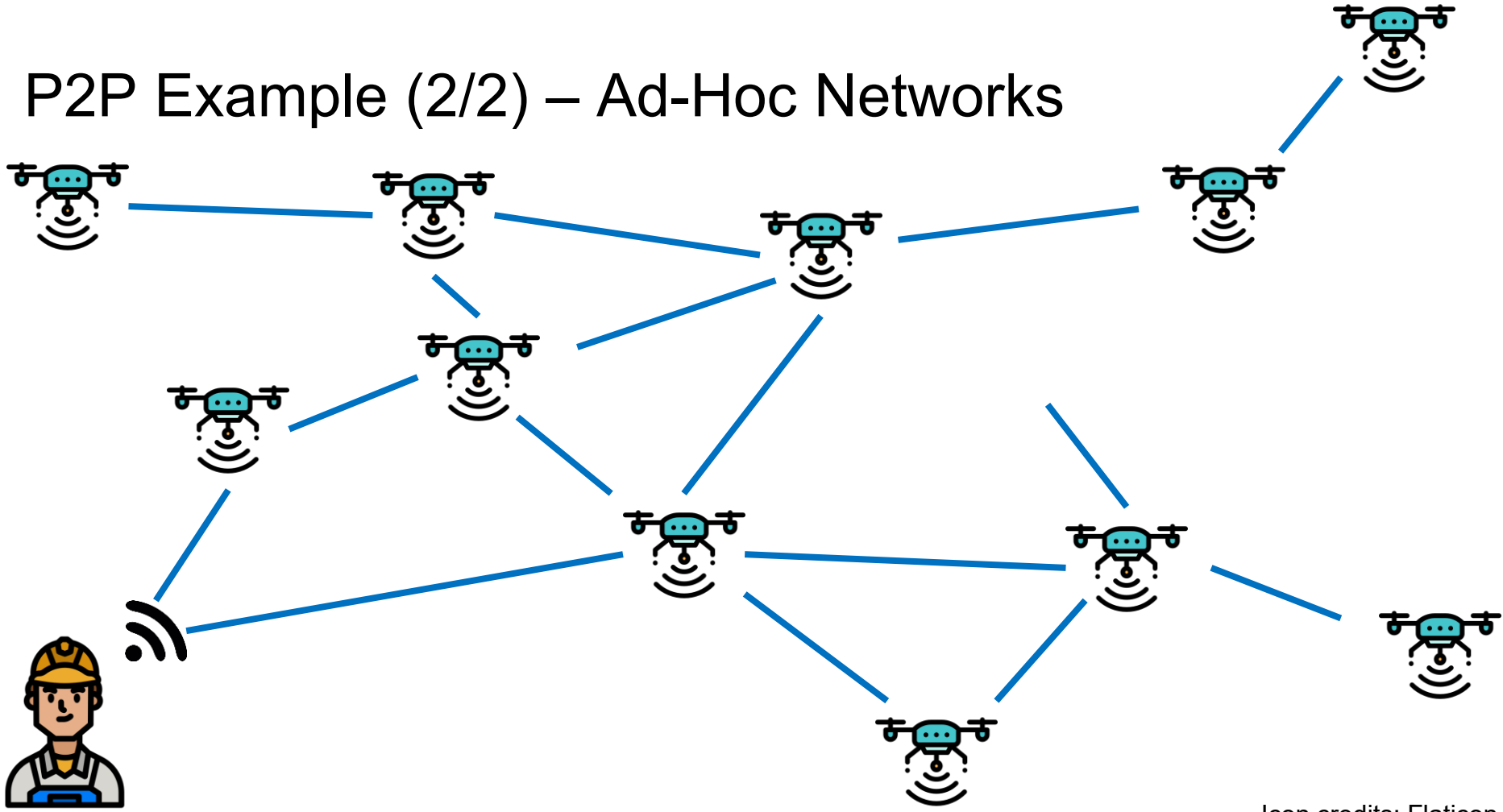
(Homework 1)

P2P Example (1/2) – Your Home & EPFL Networks



Icon credits: Flaticon

P2P Example (2/2) – Ad-Hoc Networks



Icon credits: Flaticon

P2P Examples – Quick analysis

- Peers may not be directly accessible
- Peers may join or leave the network at arbitrary times
- We need to route packets through the system

Some differences:

- Churn
- Node mobility / network reconfiguration
- Protocols / Physical Layer / etc.
- Bandwidth

Naive routing – don’t do this at home

Nodes advertise a distance to other nodes

B → D = 1

A → D = 2 (through B or C)

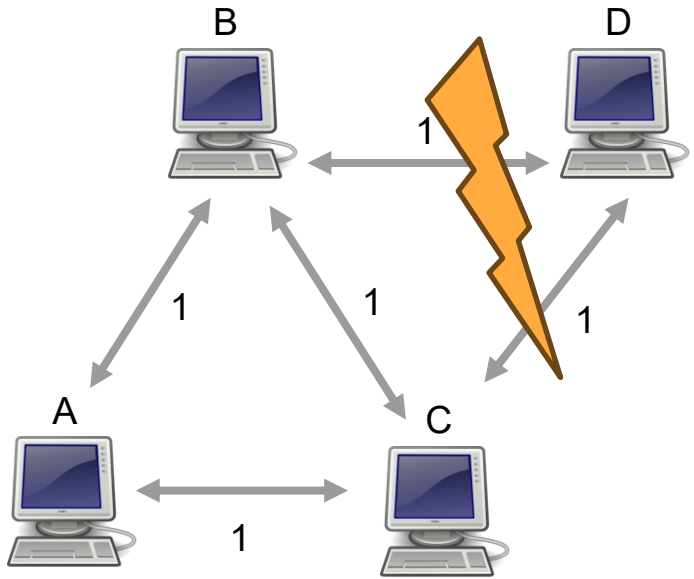
C → D = 1

On link failure, B updates:

B → D = 2 (through C)

Then C updates:

C → D = 3 (through B)



Reaching arbitrary peers in a network : AODV

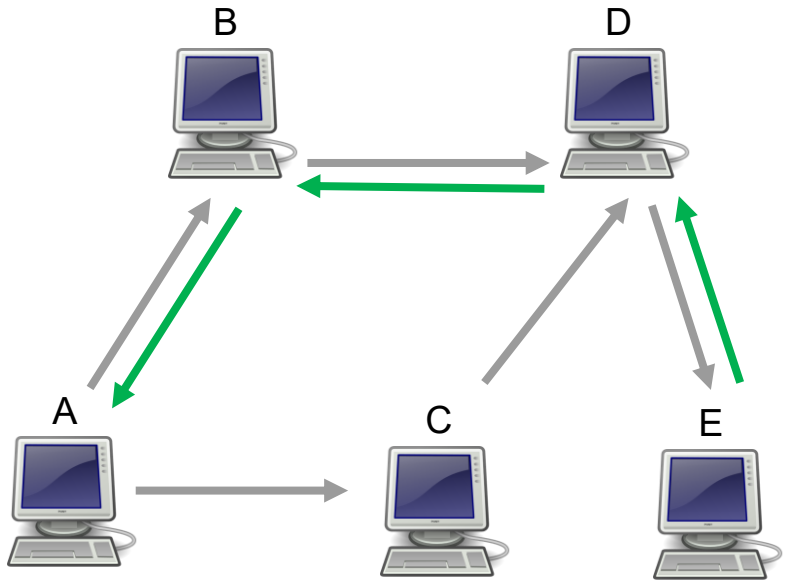
Ad-hoc On-demand Distance Vector

Key idea: Flooding search for a node (e.g. E)

Nodes remember where the search came from
... And build a return path

A → B → D → E
A ← B ← D ← E

Reactive (on-demand) routing, cached
Used in the ZigBee wireless protocol



Reaching arbitrary peers in a network : DSDV

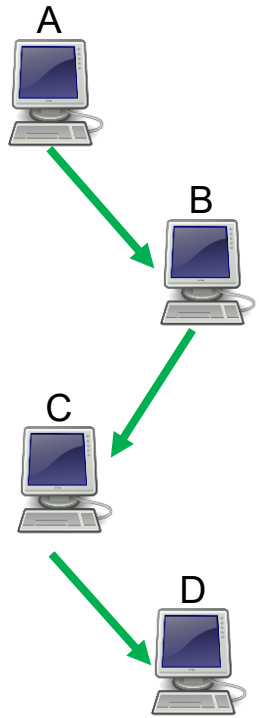
Destination-Sequenced Distance Vector

Key idea:

- Store next hop for any destination ($O(n)$)
- Version (“sequence”) routing table entries

Each node periodically broadcasts its existence:
Flood the network, with increasing sequence numbers

$O(n^2)$ traffic, superseded by newer protocols,
versioning idea lives on !



Quality factors in ad-hoc routing

- Speed of convergence
- Loop-free
- Traffic at rest (maintenance)
- Traffic during updates
- Robustness to churn & movement

Compact Routing & Structured Search

$O(\log n)$, here we come !

General Approach

- Build a structured *overlay network*

- Enables significant efficiency gains

We'll pay a price:

- More engineering effort
- Nodes will need local state
- Constant fight against churn
- Loss of generality

Distributed Hash Table

Local hash tables need:

- “Good” hash function
- Random-access memory
- Not too full

Distributed hash tables considerations:

- What do we need from the hash function ?

  Avoid collisions, not time-sensitive

  → Cryptographic hash, well distributed

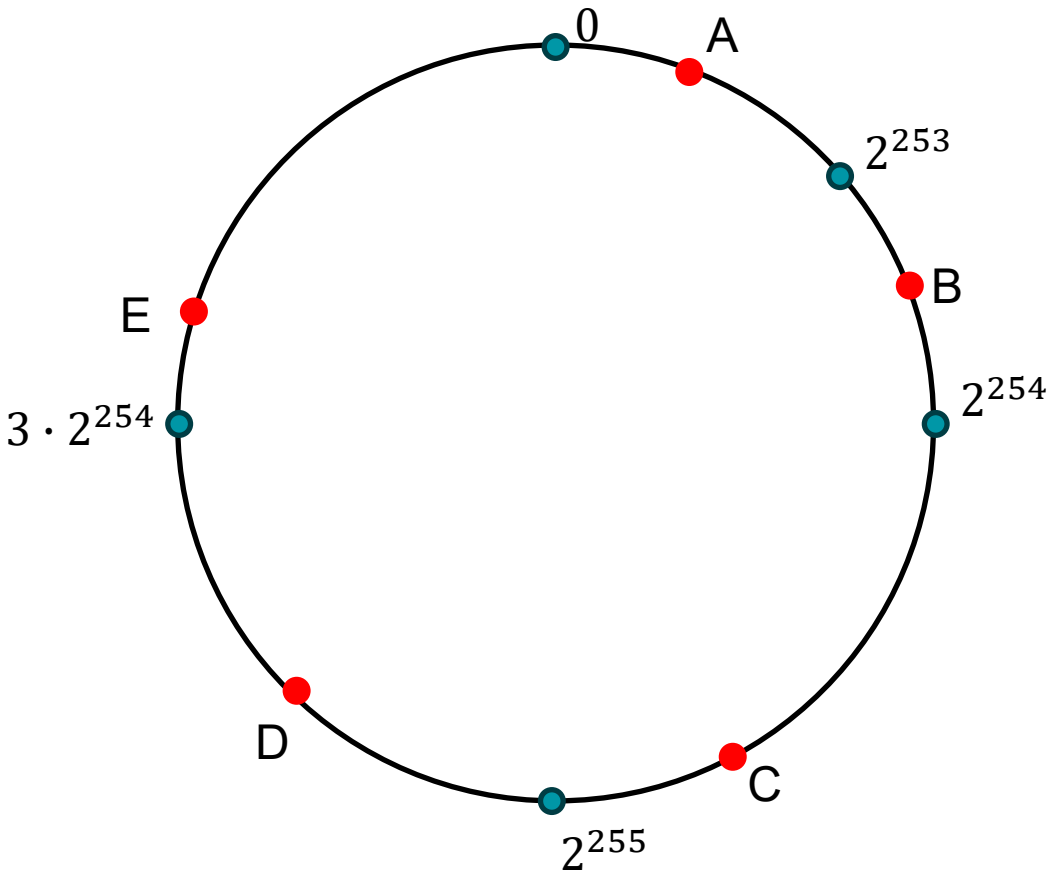
- What are we missing ?

  → RAM

Chord DHT

- Hash into a collection of RAMs
- Circular hash ID space (e.g., SHA-256)
- Each node has a pseudo-random hash ID

What should go into that ID ?
Public Key !



Chord DHT

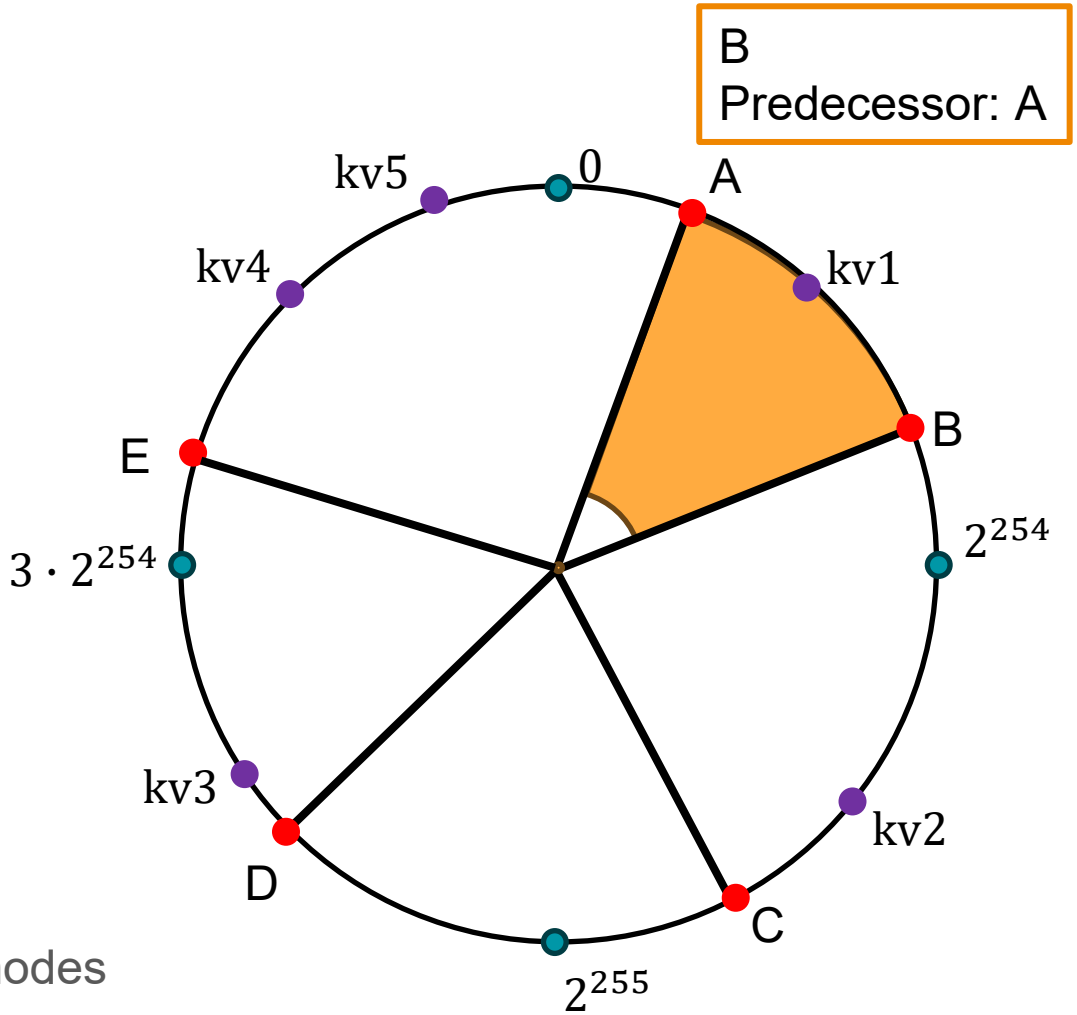
How do we approximate RAM ?

- Divide the space up !
- Each node owns the space from its predecessor

API:

- PUT(key, value)
- GET(key) → value / error

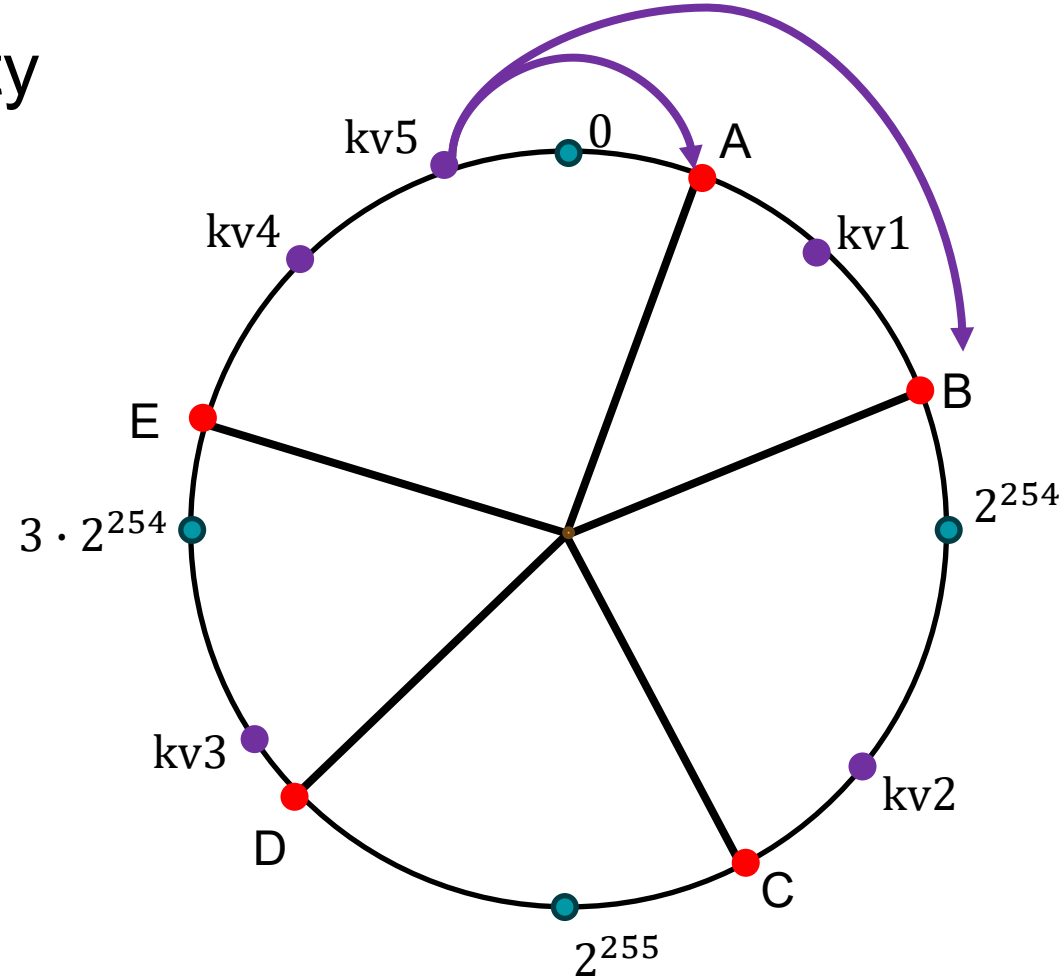
Keys use same hash function as nodes



Chord DHT – Reliability

How do we prevent data loss ?

- Redundancy – factor r
- Copies are stored by “owner” node + $(r-1)$ successors

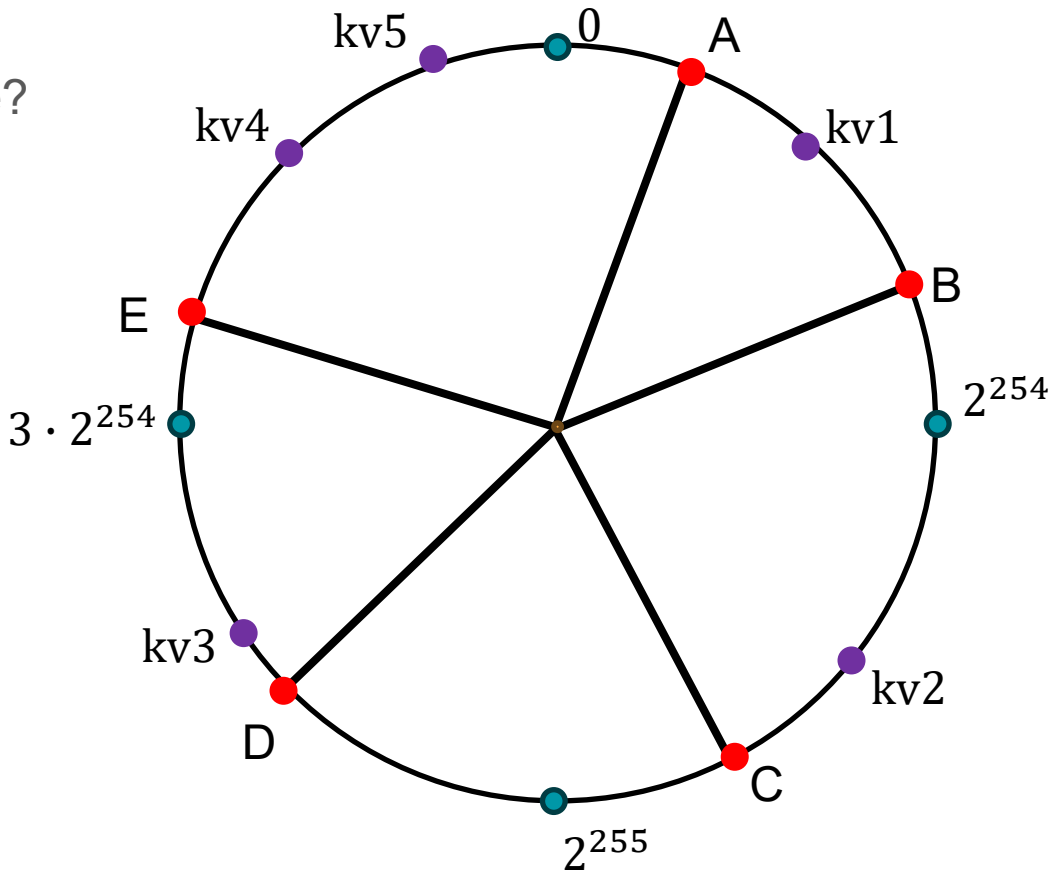


Chord DHT – Load

What is the expected load per node?

n – # of nodes
m – # of key-value pair
r – redundancy factor

Load $\sim \frac{r \cdot m}{n}$

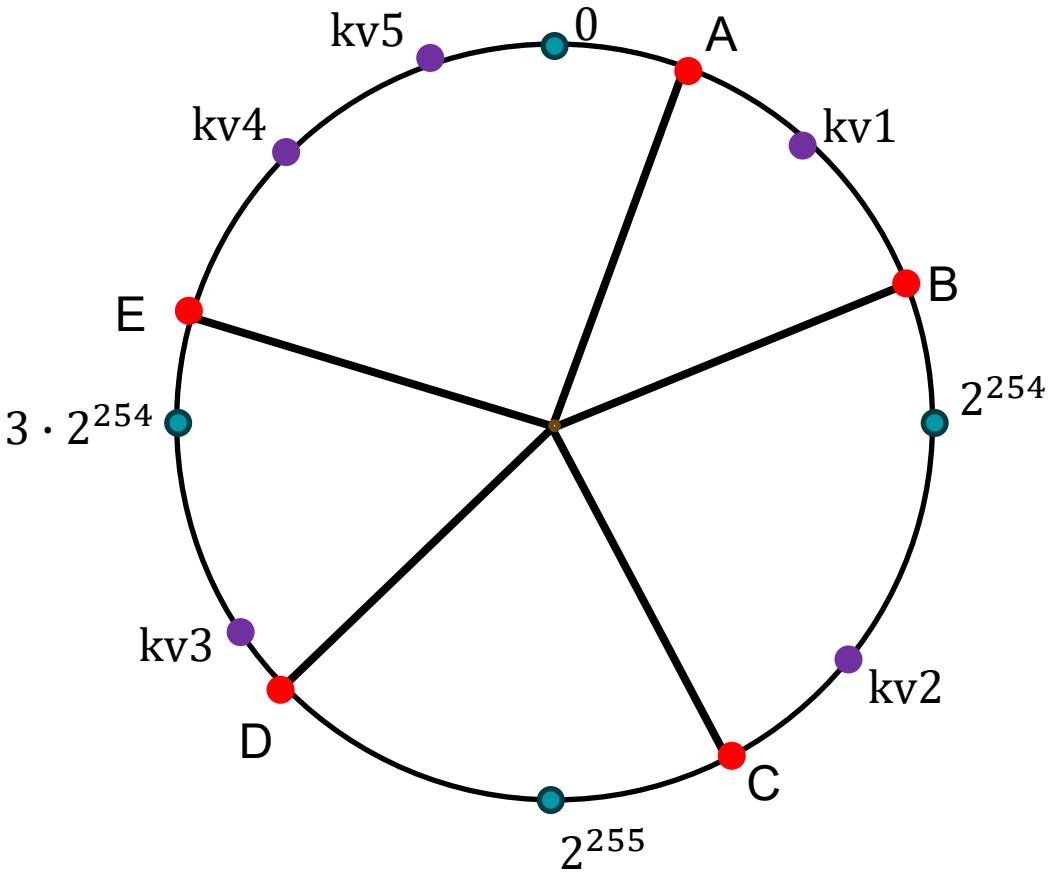


Chord DHT – Performance

How do we make this $O(\log n)$?
(in storage, network, etc.)

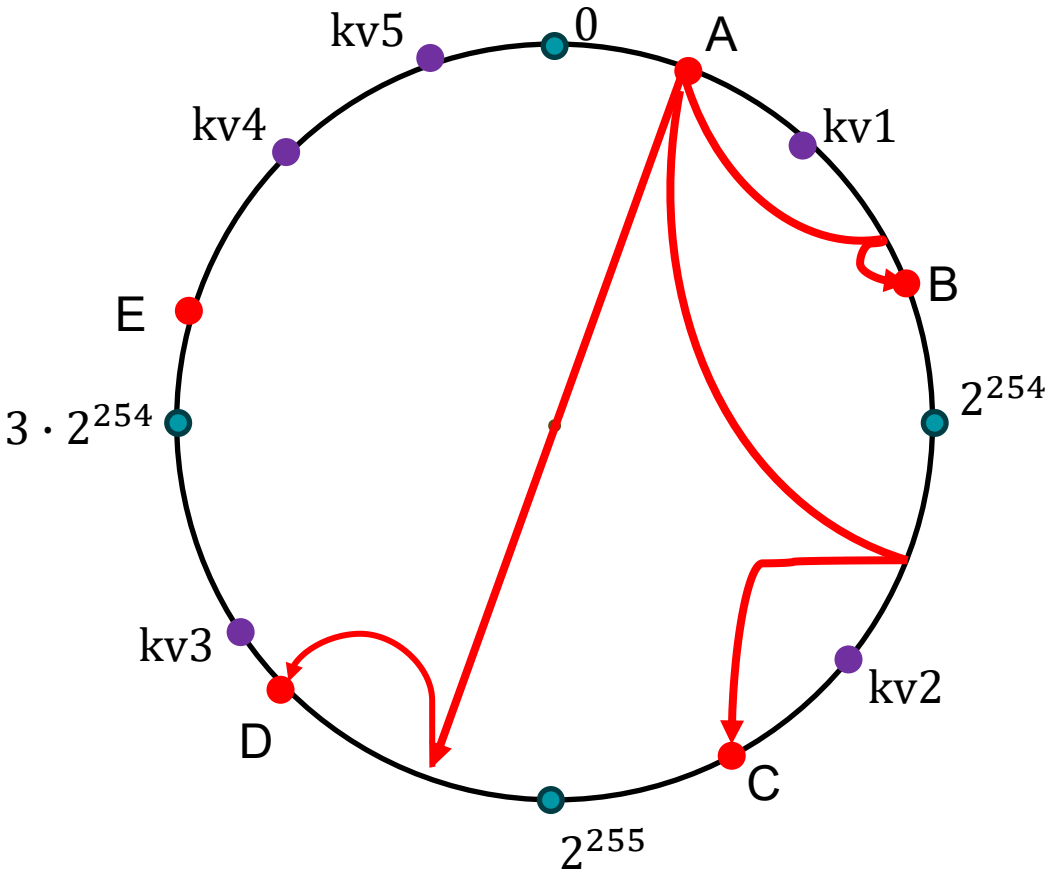
- Using only successors:
  $O(1)$ routing table size
  $O(n)$ access ☹

- Binary search ?
  Finger tables !



Chord DHT – Finger tables

Distance	Bucket
1	(successor) = B
½ circle	D
¼ circle	C
⅛ circle	B
...	...



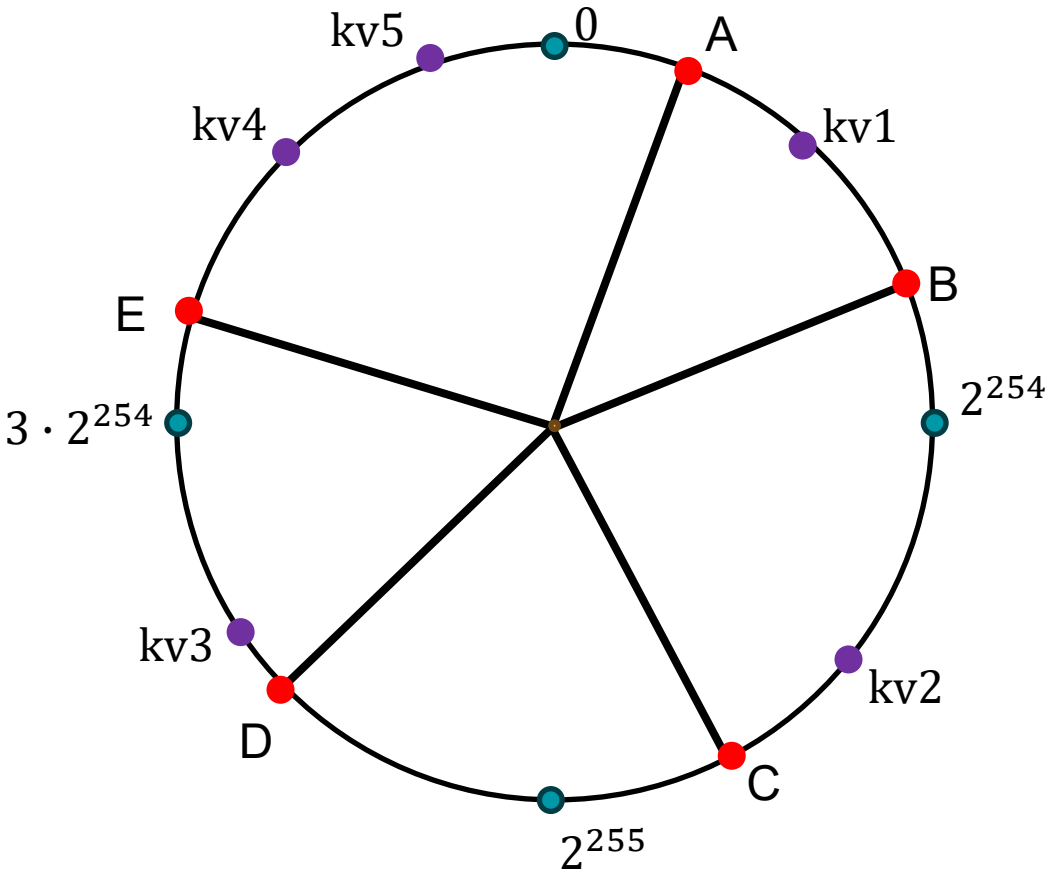
Chord DHT – Churn

Need to handle:

- Concurrent joining
- Nodes leaving (gracefully)
- Nodes leaving (unresponsive)

Approach:

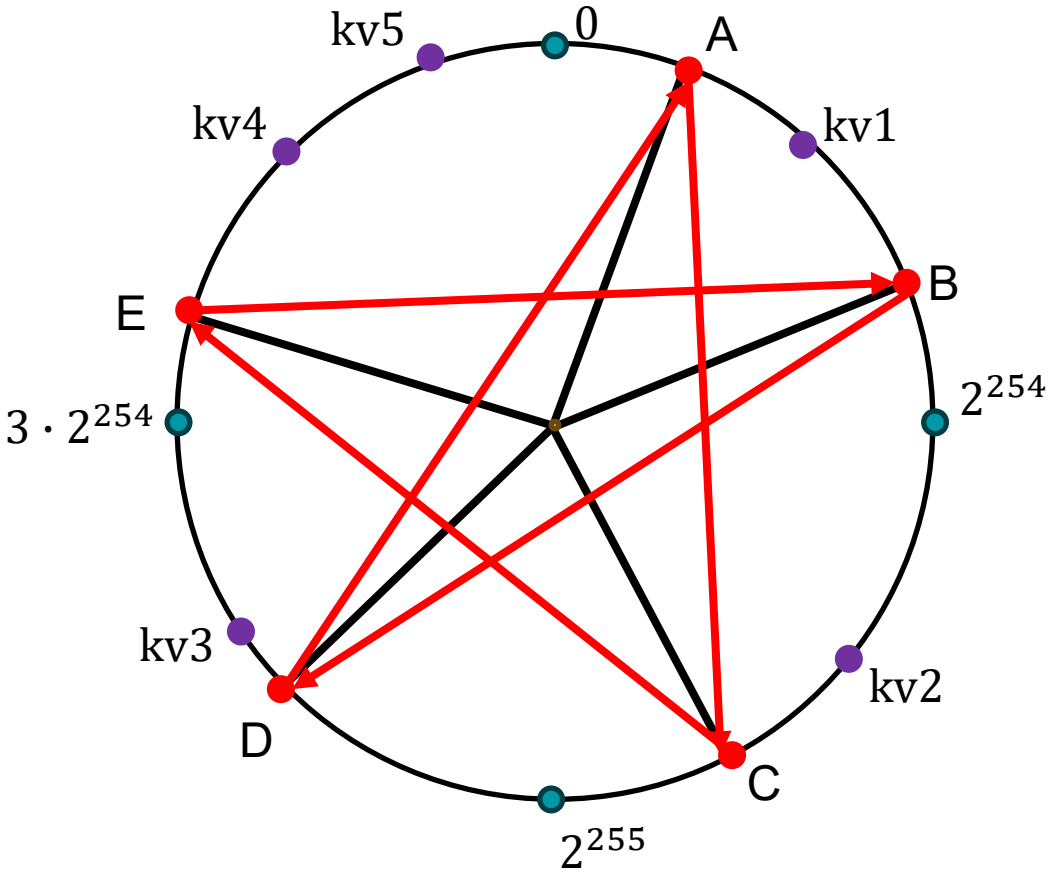
- Split correctness & performance
- Transient failures can be retried



Chord DHT – Degenerate cases

Network partitions can lead to some (transient) degenerate cases.

Where:
B's successor is D
D's successor is A
A's successor is C
C's successor is E
etc.



Chord DHT – Possible attacks

- Sybil attacks
- Eclipse attacks
- Churn attacks
- Adversarial routing
- Denial of Service

Next steps - Readings

Mandatory:

- DSDV: Routing over a Multihop Wireless Network of Mobile Computers
- Chord: A Scalable P2P Lookup Service for Internet Applications

Recommended (Engineering):

- The Babel Routing Protocol (RFC 8966)
- Kademlia: A Peer-to-Peer Information System Based on the XOR Metric

... and a few others for the curious among you ...

→ Use Friday’s session to ask questions