Beyond Replicated Storage: Eventually-Consistent Distributed Data Structures

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  - Based on wireless sensor networks:
    - Hundreds or even thousands of nodes in a network
    - A single node is severely constrained in resources

Extreme distributed systems

- More complex than sense-and-send:
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  - Analyzing and deciding
  - Actuating

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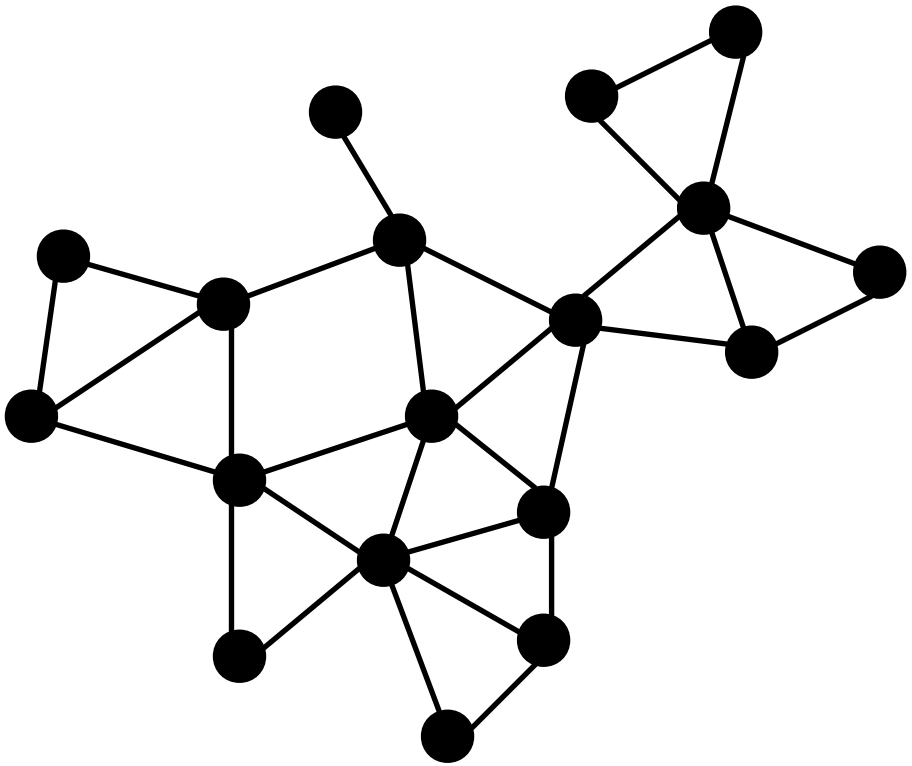
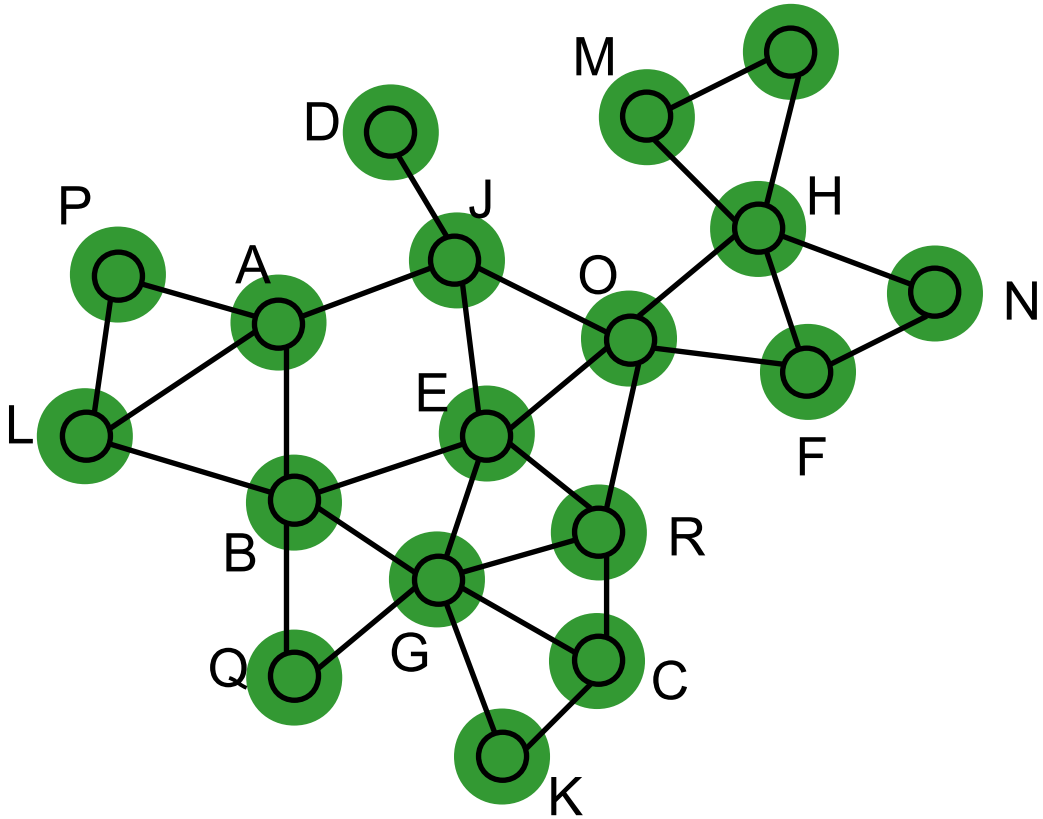
  } **collaborative**
- Subject to various challenges:
  - Resource constraints
  - Unreliable communication
  - Interactions with the surrounding environment
- Distributed algorithms are increasingly complex
  - ➔ e.g., employ specific organizations.

Cluster hierarchy



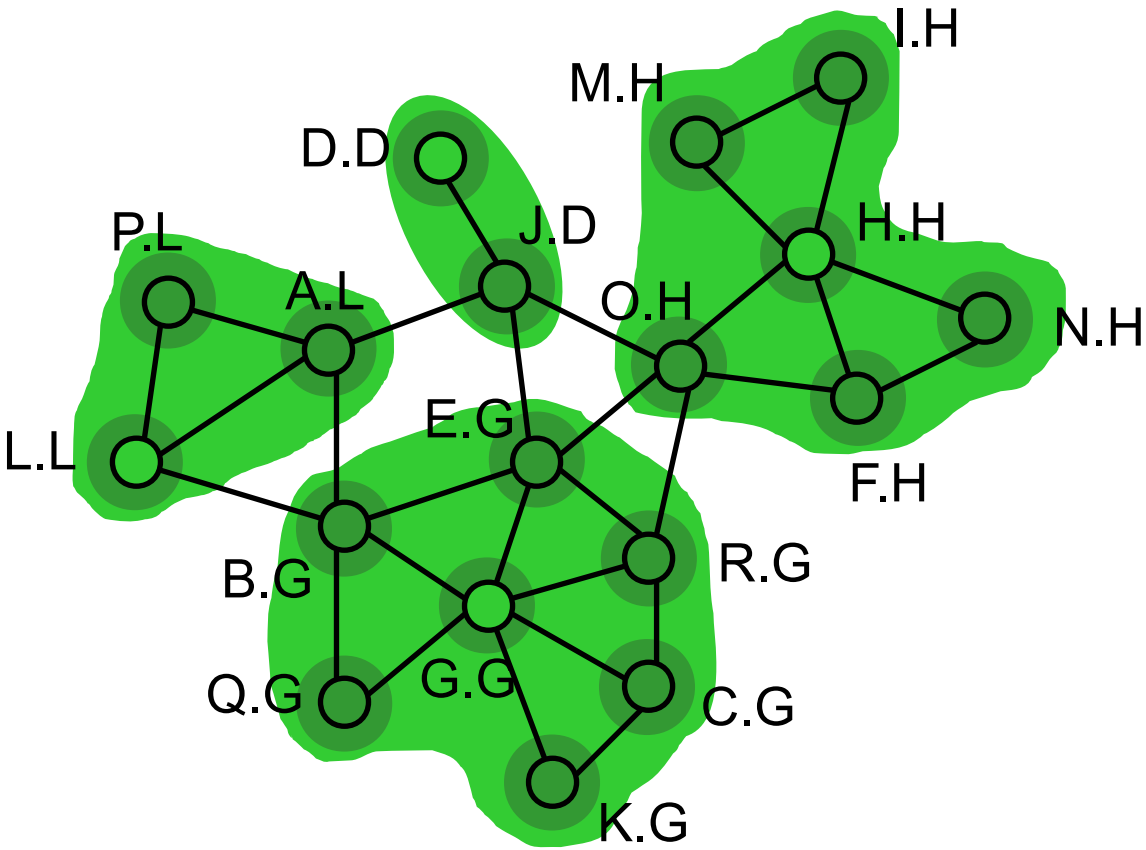
Wireless connectivity between nodes.

Cluster hierarchy



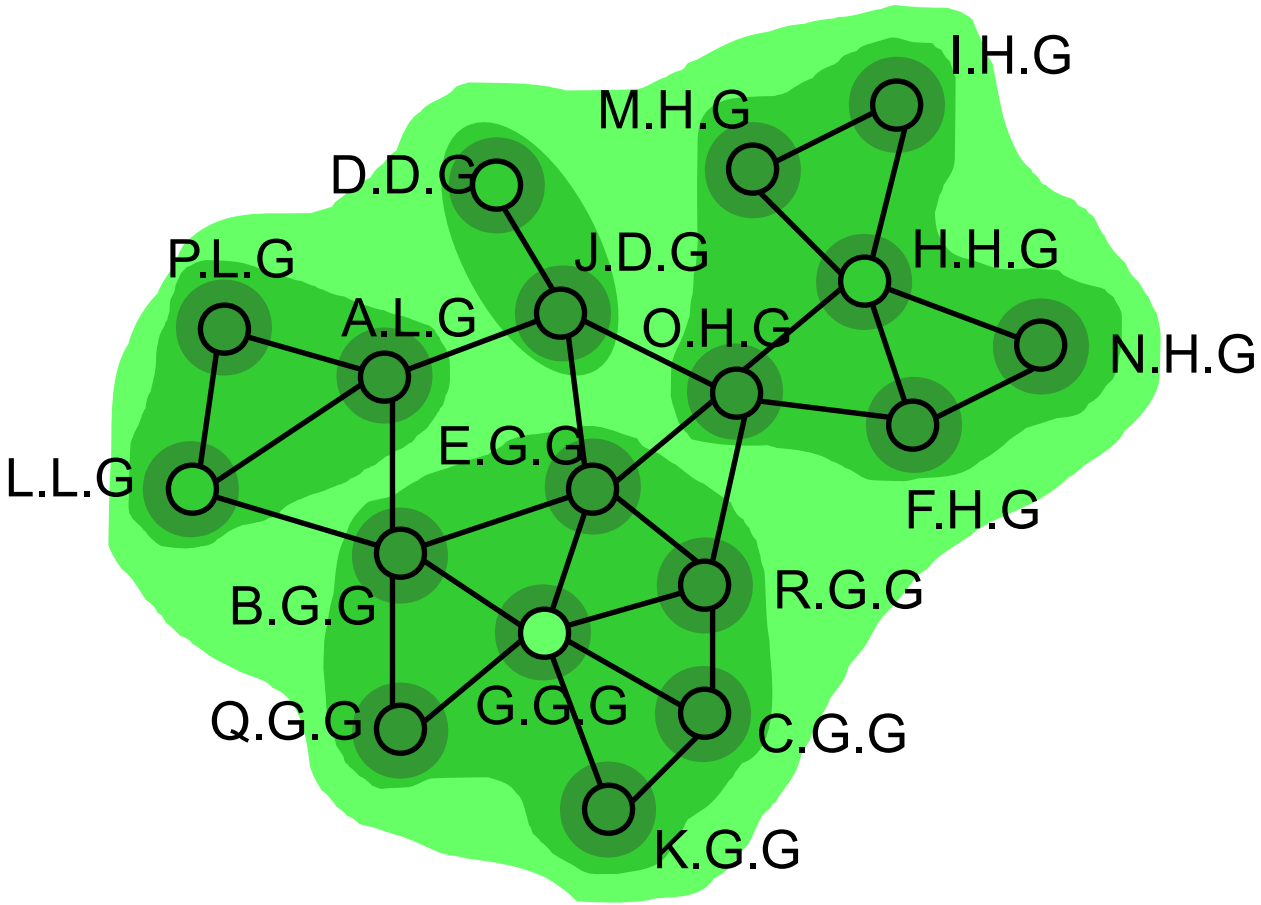
Each node forms a level-0 **cluster** of which it becomes the **head**.

Cluster hierarchy



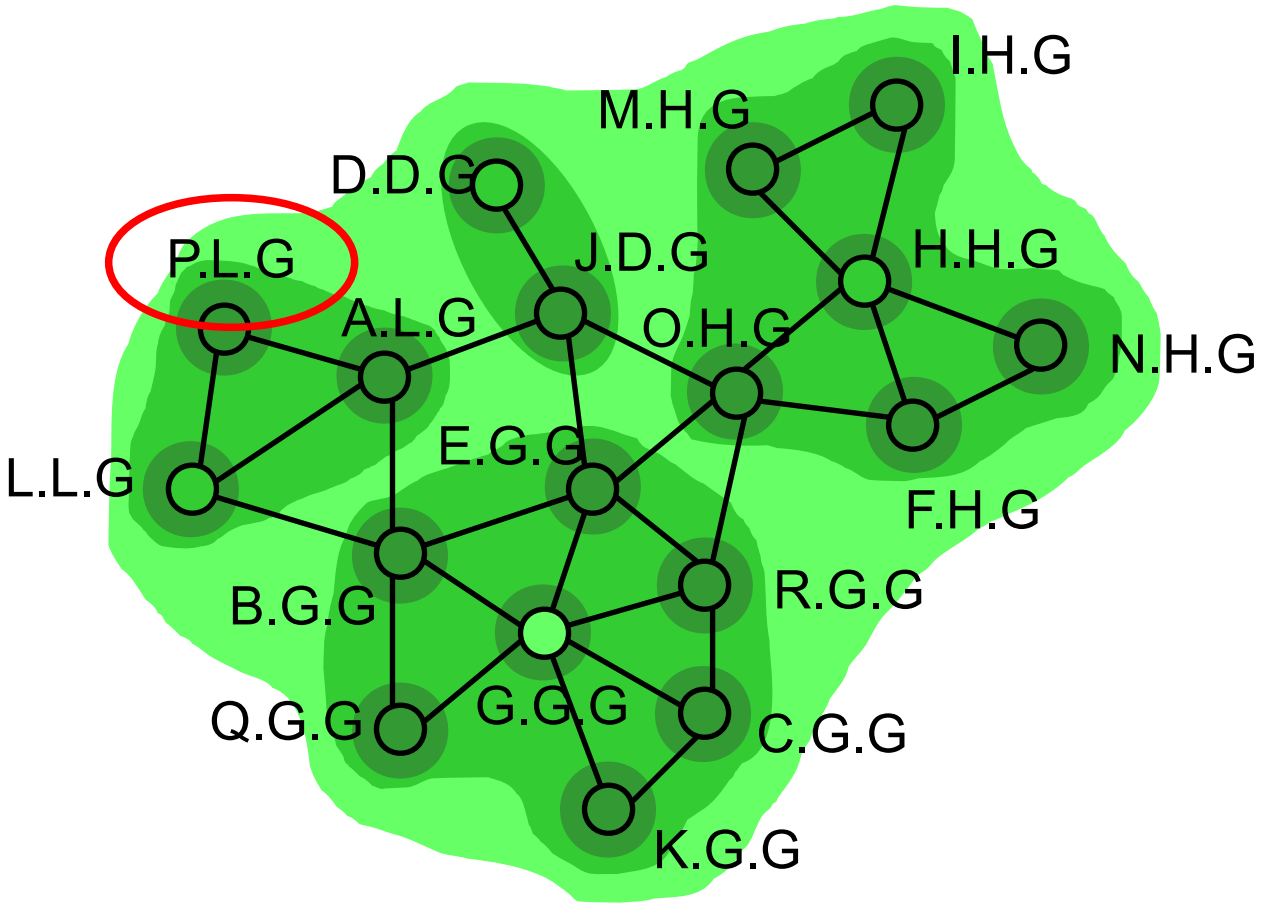
Proximate level-0 clusters are grouped into level-1 clusters.

Cluster hierarchy



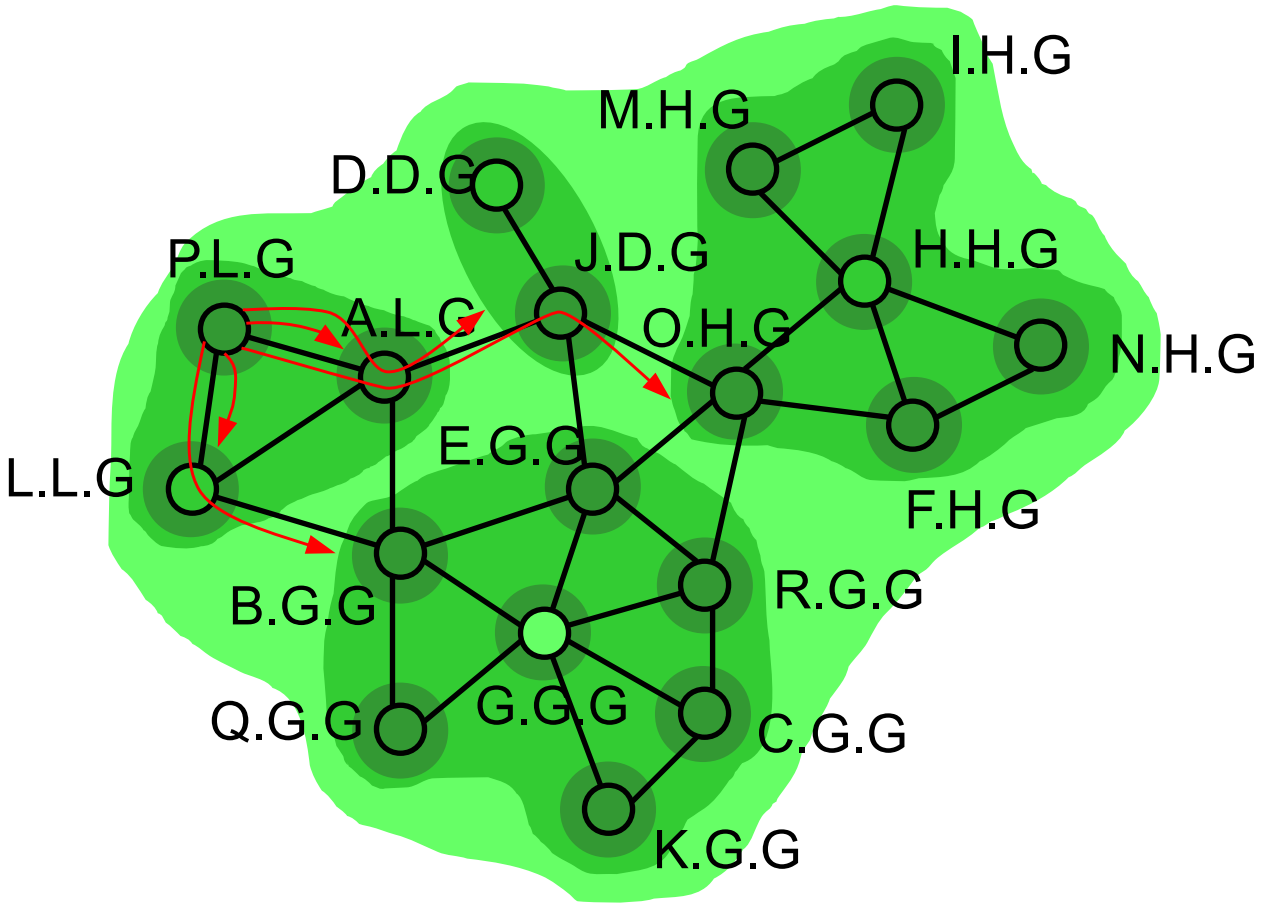
And so on at higher levels, typically until a single cluster remains.

Cluster hierarchy



The membership of a node in the hierarchy is reflected in the node's **label**.

Cluster hierarchy



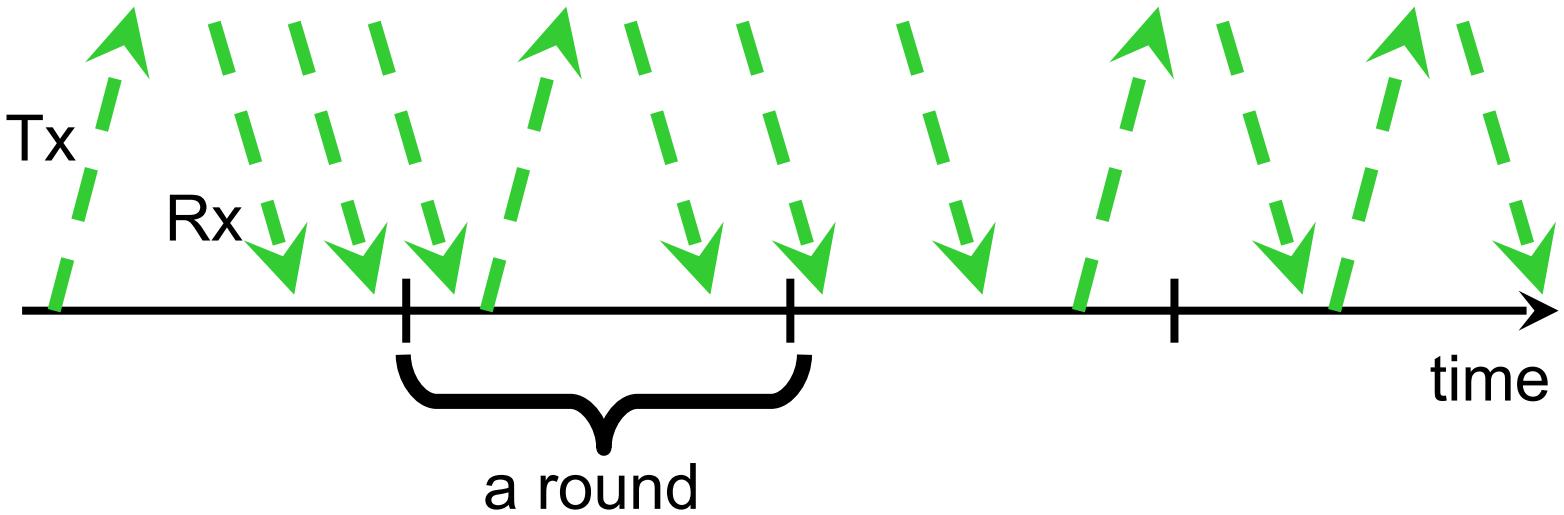
Each node also maintains information for each sibling cluster in the hierarchy (e.g., a **routing entry**).

The problem

- Using the hierarchy is relatively easy:
  - Routing
  - Aggregation
  - In-network storage
- Maintaining it is a different story.
  - Connectivity changes
  - Node failures & arrivals
  - Nodes should be autonomous

General scheme – gossiping

- Each node maintains its state which it occasionally updates.
- For communication:
  - Each node operates in rounds.
  - In each round, it broadcasts its state to its neighbors.
  - It also receives the neighbors' states, which it merges with its own one.



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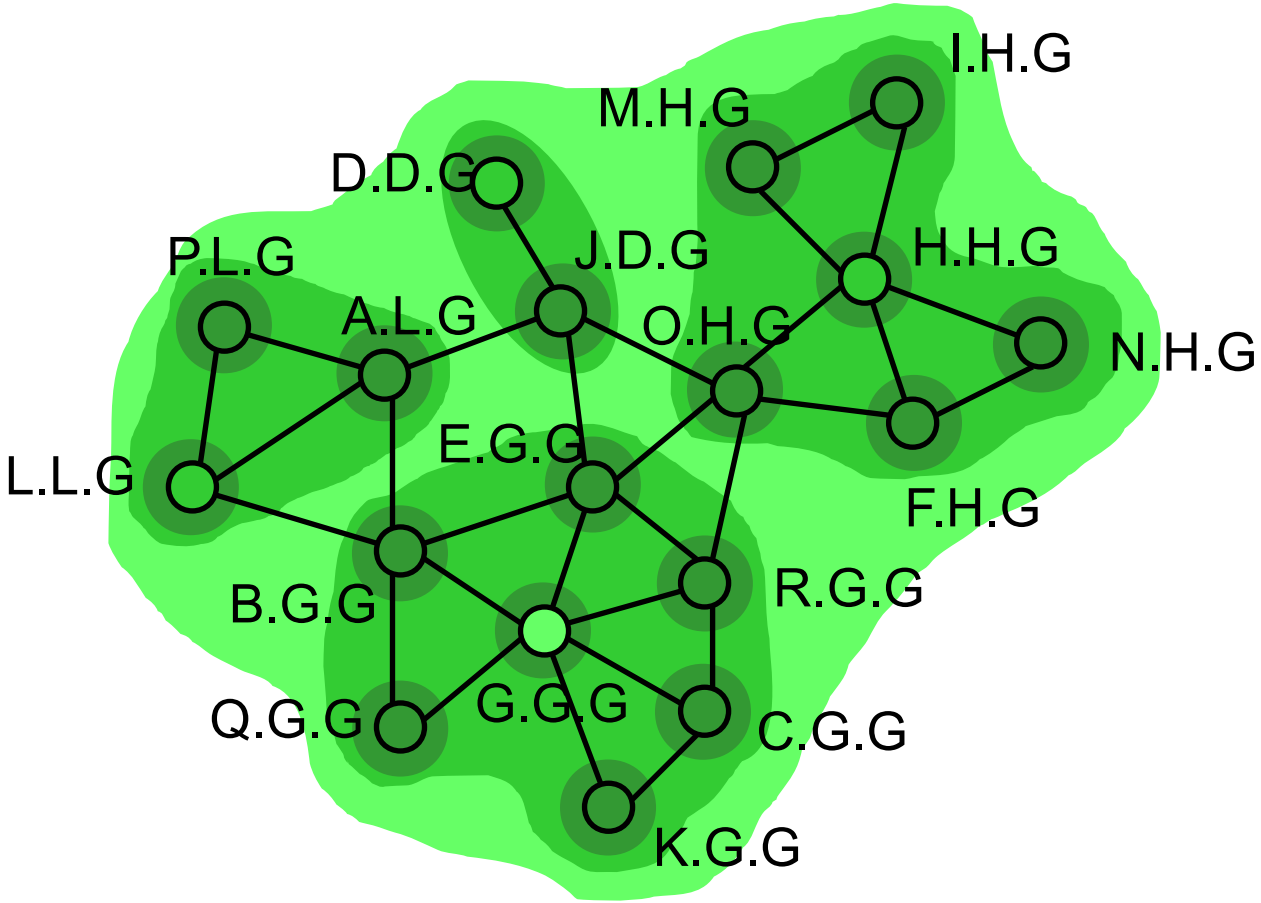
Let's thus take a look at the problem of cluster hierarchy maintenance from the eventual consistency perspective.

EC perspective

- We treat the cluster hierarchy as a distributed structure.
- The sate of each node
  - label
  - routing table

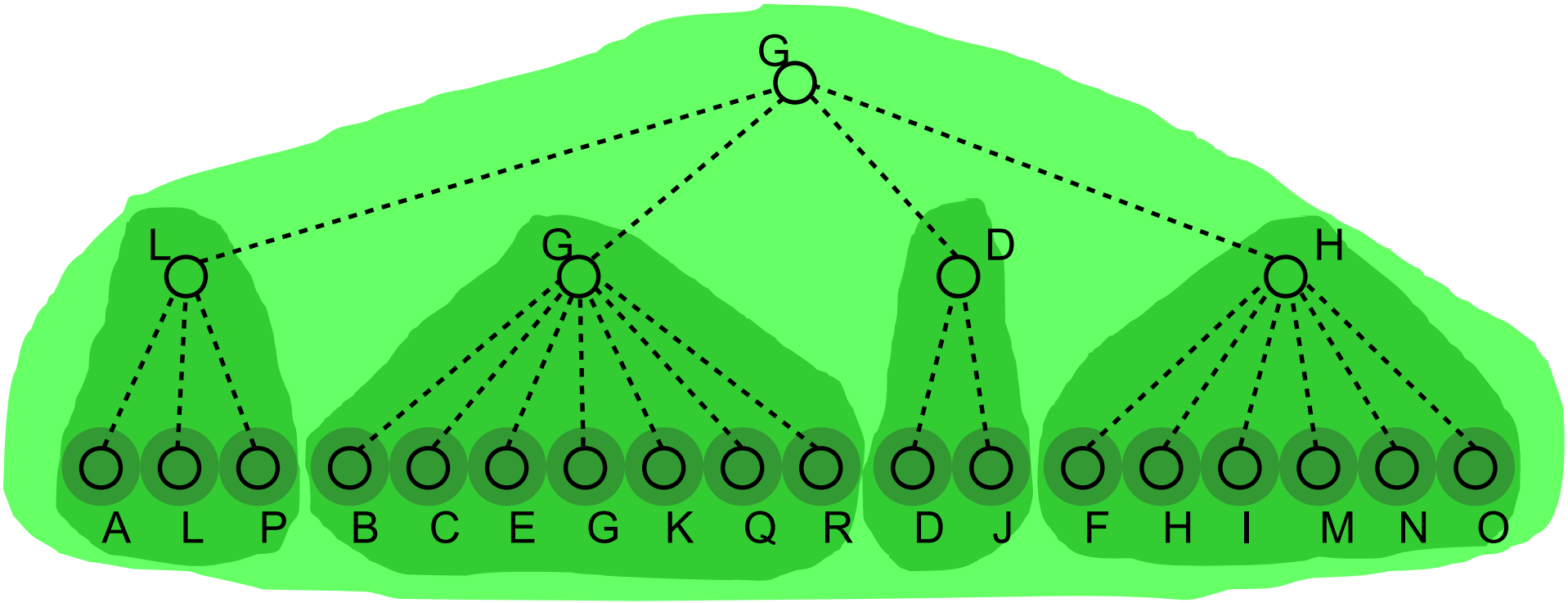
  is a part of this structure.
- Each node can autonomously update its local state:
  - Locally altering the structure.
- The updates propagate through gossiping:
  - Eventually the structure becomes consistent globally.

EC perspective



Consider node labels.

EC perspective



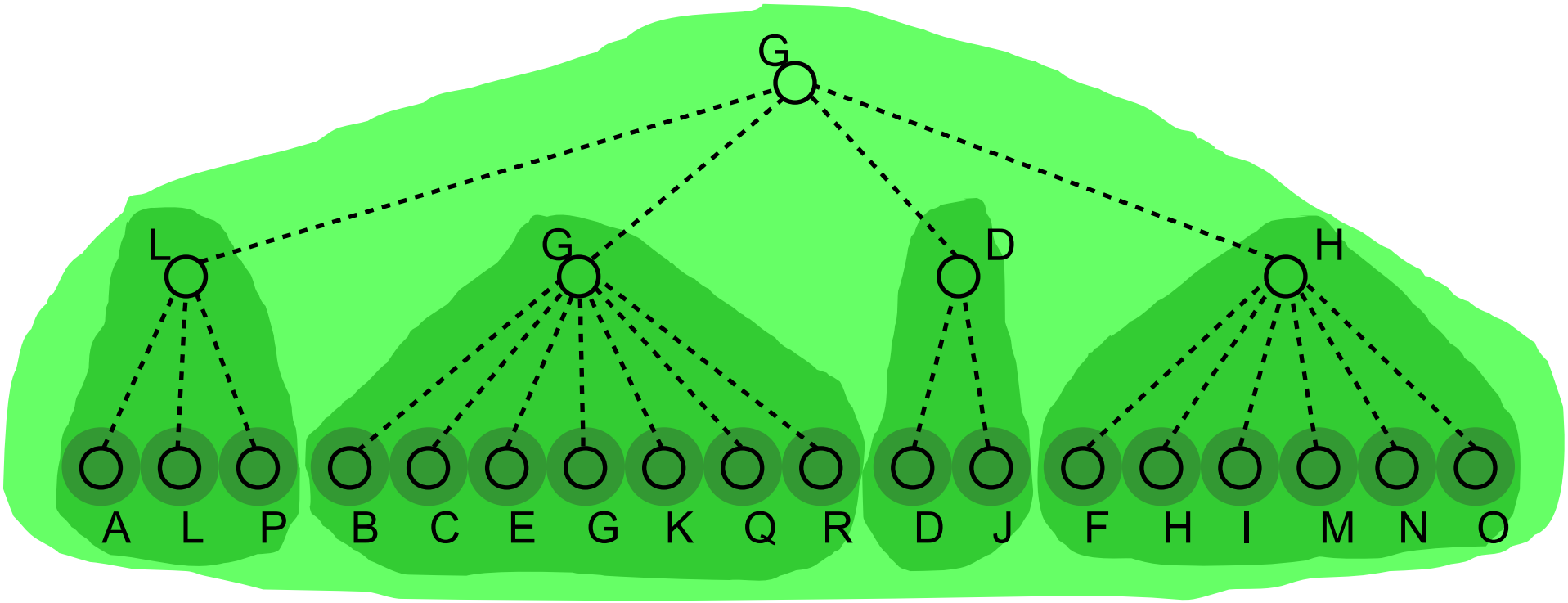
They can be viewed as a distributed tree.

EC perspective

- What is different from the “traditional” model?
  - The state of each node is **not a replica**.
  - On the contrary:
    - Some of its parts are unique.
    - Some are replicated at other nodes (to a varying degree).
  - On the global scale the states of all nodes should form a coherent structure.

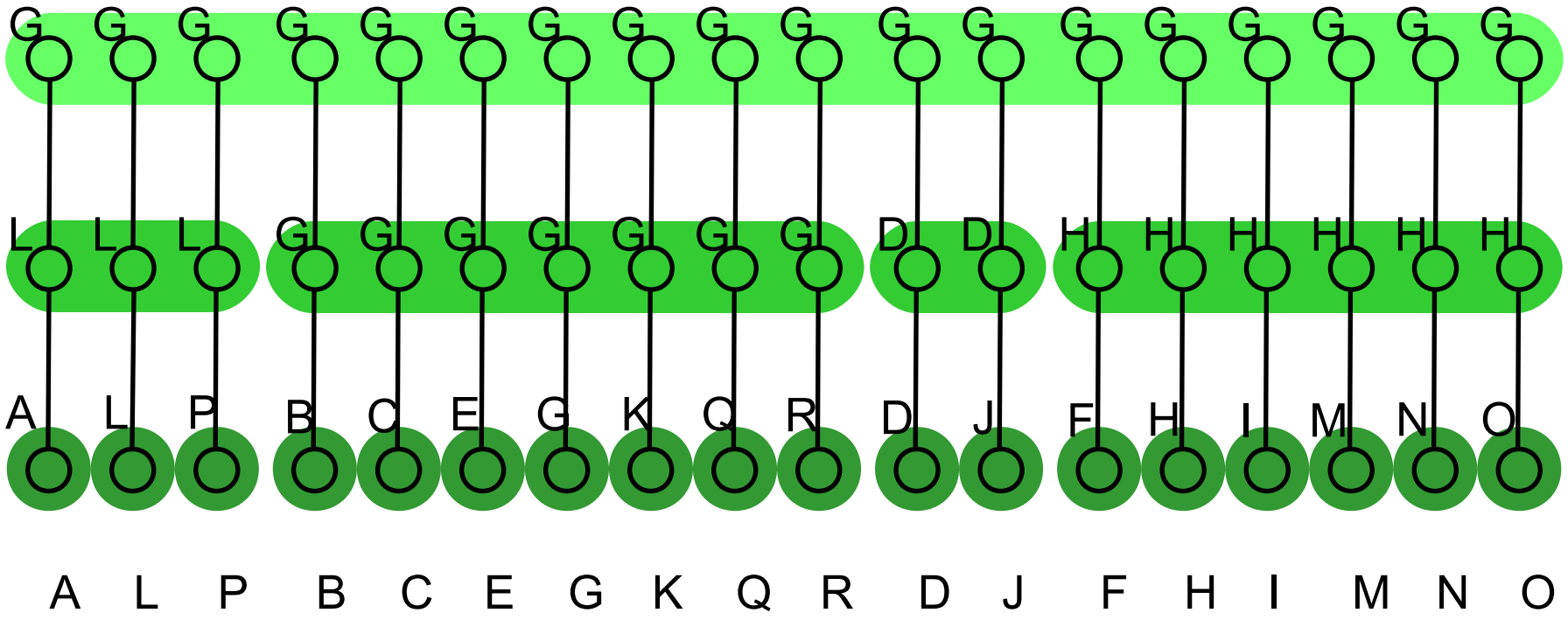
EC perspective

Logical view:



EC perspective

Physical view:



EC perspective

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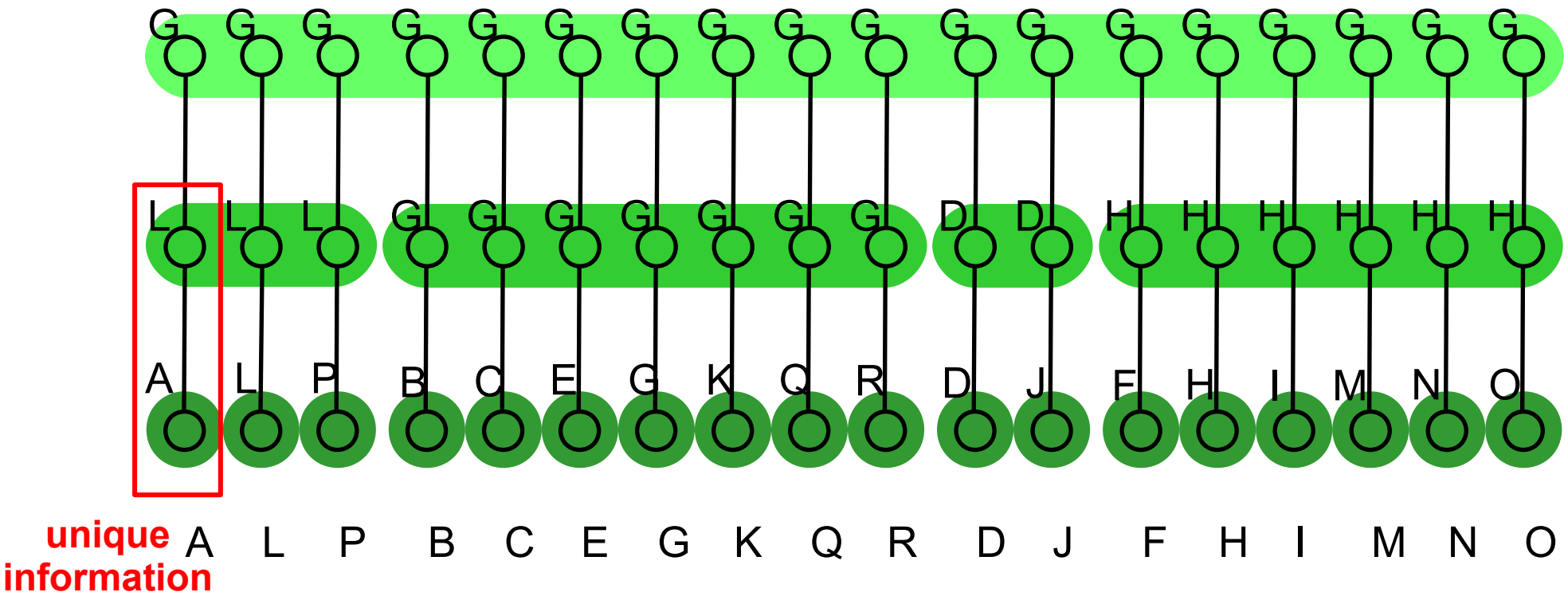
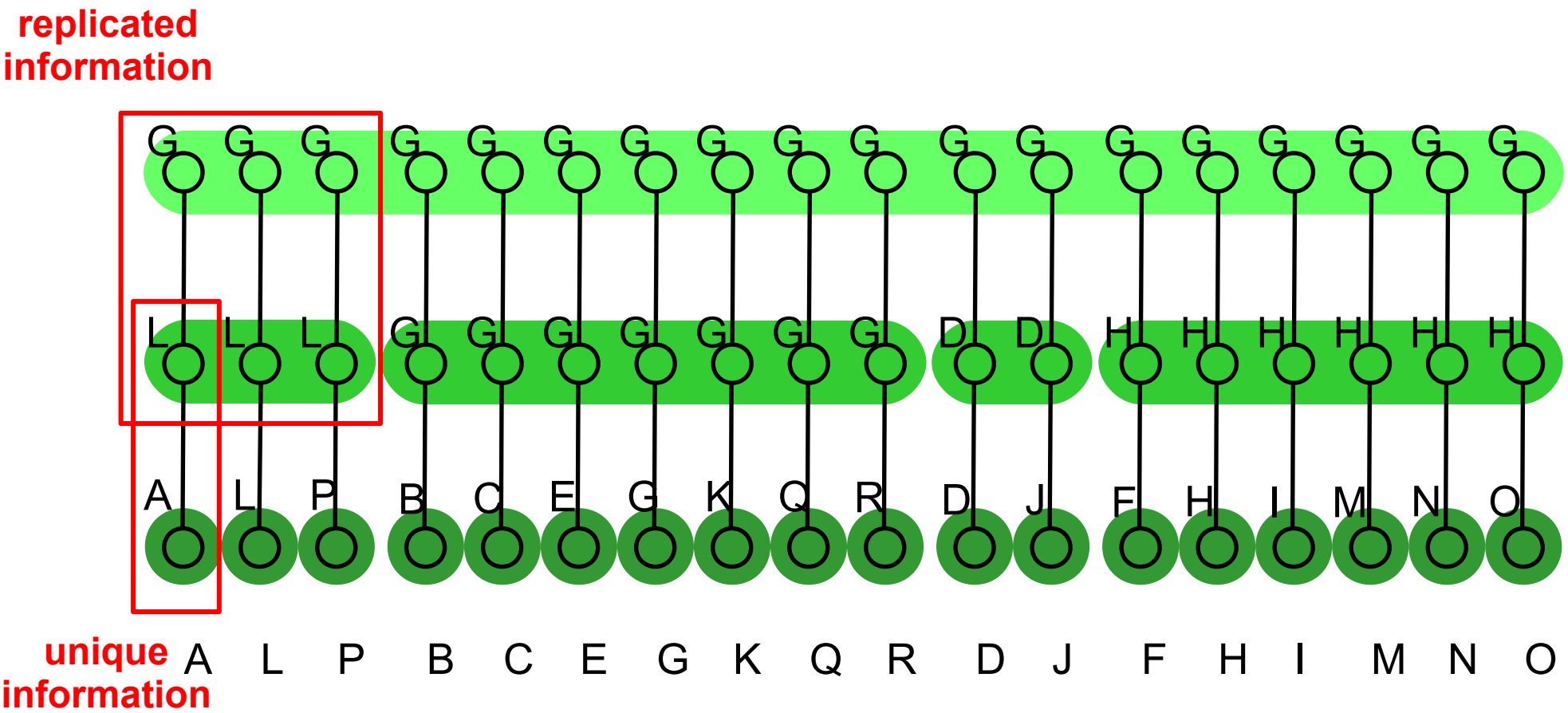


EC perspective

Physical view:



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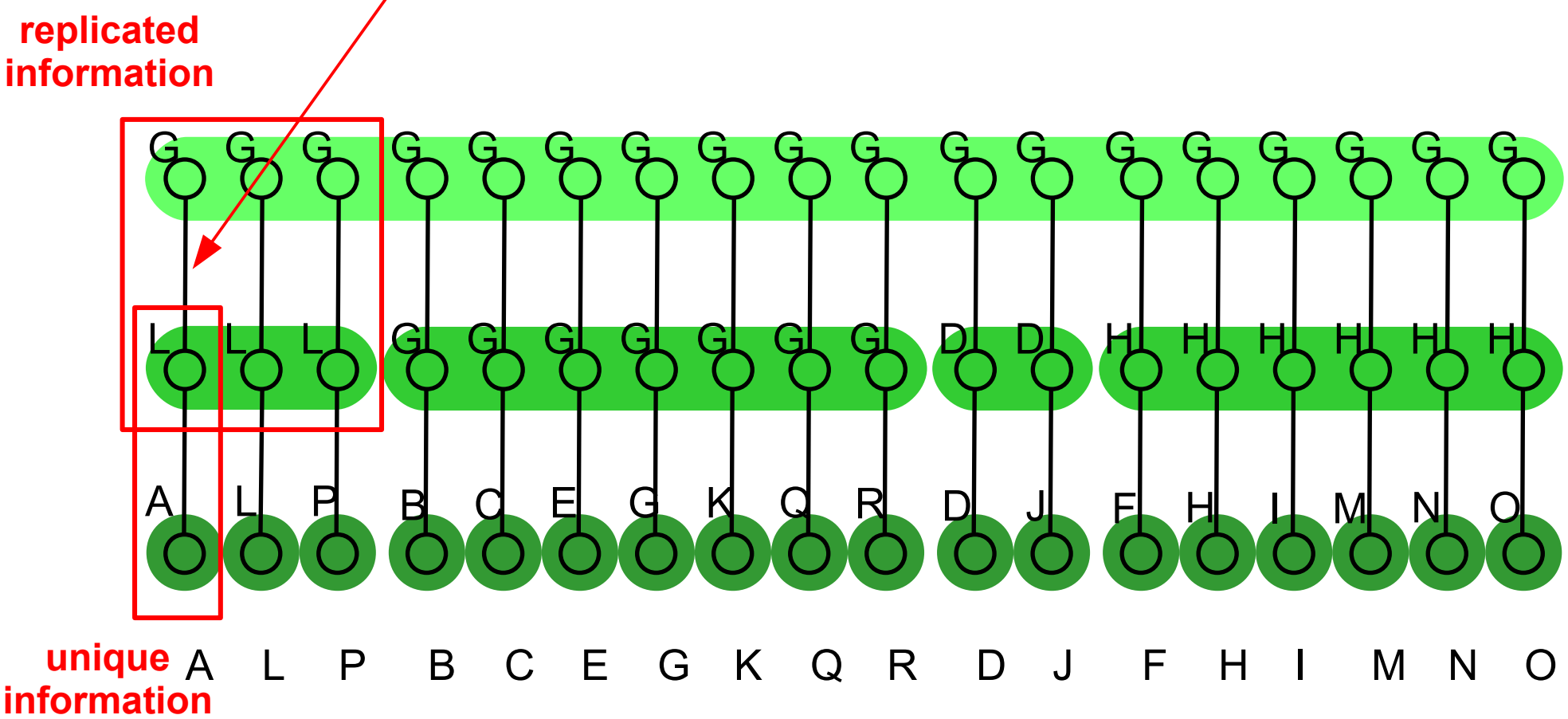
Physical view:

When this changes at one node, the other nodes must update their state accordingly

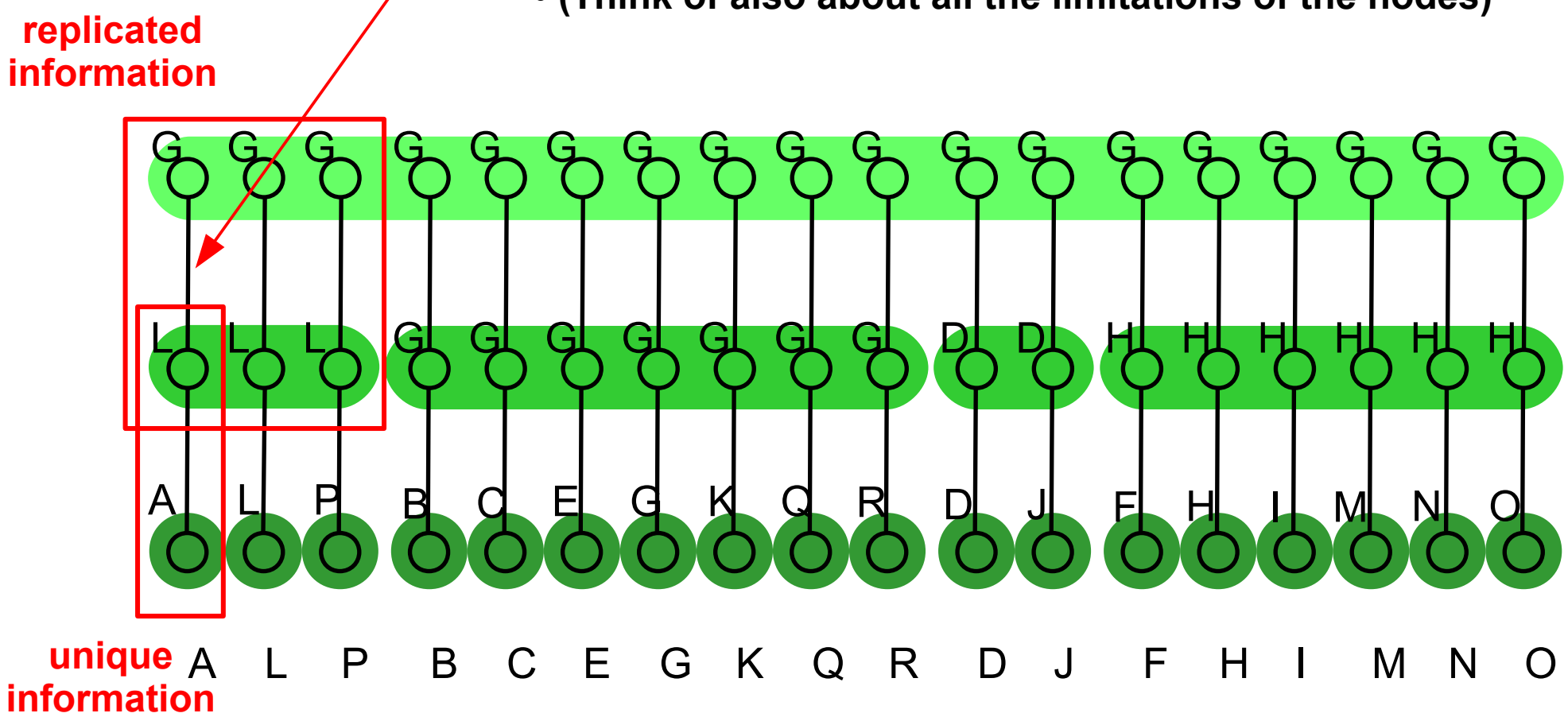


EC perspective

Physical view:

When this changes at one node, the other nodes must update their state accordingly, **but**

- **Updates can be concurrent**
- **They are often not independent**
- **Propagate lazily**
- **(Think of also about all the limitations of the nodes)**



EC-related challenges

- How to decide that a given piece of the distributed structure should be updated?
- How such updates should be performed and which node(s) should do them?
- How can other nodes detect and merge the updates to their corresponding pieces of the distributed structure?
- (How to do this under constrained resources?)

Our solution

- Details, for instance, in:
  - K. Iwanicki and M. van Steen. **“Gossip-based self-management of a recursive area hierarchy for large wireless sensornets.”** *IEEE Transactions on Parallel and Distributed Systems*, 21(4):562–576, April 2010.

or

  - K. Iwanicki. **“Hierarchical Routing in Low-Power Wireless Networks.”** *PhD thesis*, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands, June 2010.

Our solution – overview

- Formalize the properties of a hierarchy as invariants, e.g.:
  1. *Level-0 clusters correspond to individual nodes.*
  2. *There exists a single top-level cluster.*
  3. *Level-i+1 clusters are composed out of level-i clusters.*
  4. *Each level-i+1 cluster has a central subcluster that is adjacent to all other subclusters of the cluster.*
- Maintaining a hierarchy = **detecting and eliminating violations of the invariants**.

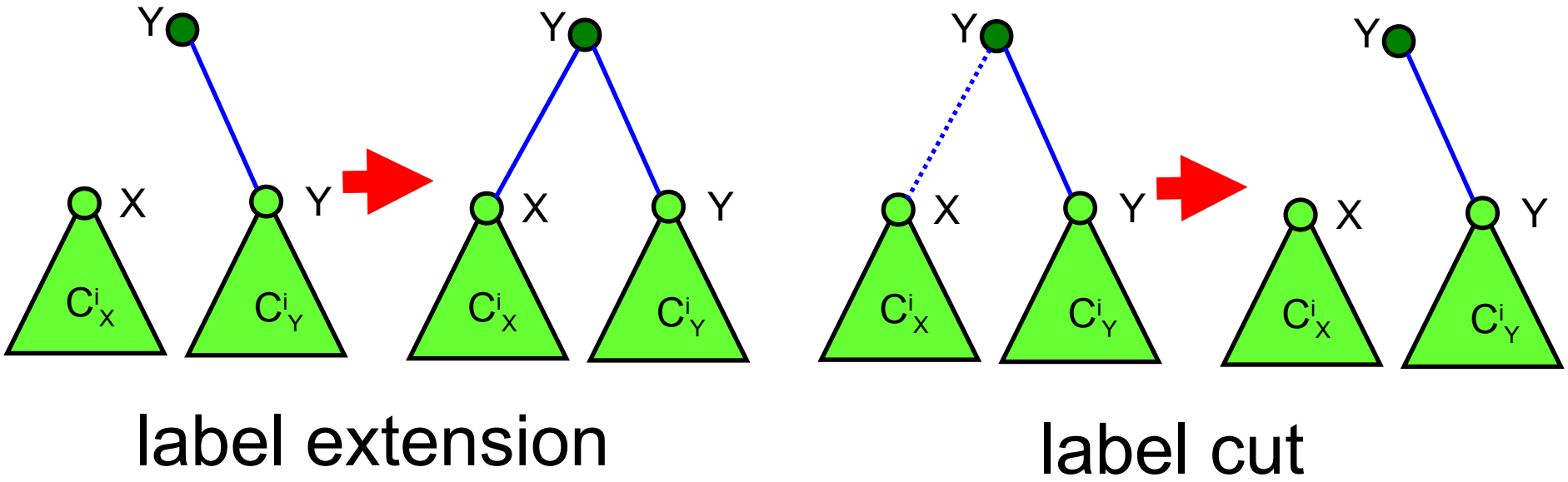
Our solution – overview

- The invariants are global
  - Have to maintained collaboratively by the nodes.
- A node's state is local
  - Each node is concerned only with those invariants that are relevant to its part of the distributed structure.
- Eliminating a violation:

  = local update operation
- Propagating the update:

  = eventually-consistent gossiping.

Our solution - example



Local operations for maintaining labels.

Our solution - example

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  - P.L.G

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- The label received in a gossip message:
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- Our label:
  - P.L.G
- The label received in a gossip message:
  - A.L.D
- What should we do:
  - leave our label as is, or
  - change it to P.L.D?

Take-home message

- Eventual consistency can offer lots of benefits to extreme distributed systems.
- Distributed data structures appear also in other fields.
- Eventually-consistent distributed data structures are poorly understood.

Thank You

Questions?

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