How to Copy Files

Yang Zhan[1,2], **Alex Conway[3,4]**, Ian Groombridge[5], Yizheng Jiao[1], Nirjhar Mukherjee[1], Michael A. Bender[6], Martín Farach-Colton[3], William Jannen[7], Rob Johnson[4], Donald E. Porter[1], Jun Yuan[5]

1 2 3 4 5 6 7

Copying is Ubiquitous and Important

cp -r

container instantiation

vmrun start

backup

Copying

Physical Copy

Copying

Physical Copy

High Latency

High Space Use

Existing Logical Copy Implementations

BTRFS

Leverages the underlying copy-on-write B-tree to implement `cp --reflink`

XFS

Uses an update-in-place B-tree but supports sharing data blocks with copy-on-write via `cp --reflink`

ZFS

Implements a limited version of copy-on-write copying via `zfs clone`

Copying

Physical Copy

Copy on Write

High Latency

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Copy on Write

Low Latency

Better Space Use

High Fragmentation

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Space Amplification and Fragmention

Dell Optiplex 790
4-core 3.40 GHz Intel Core i7 CPU
4GiB RAM
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Init: 64 4MiB files with random data.
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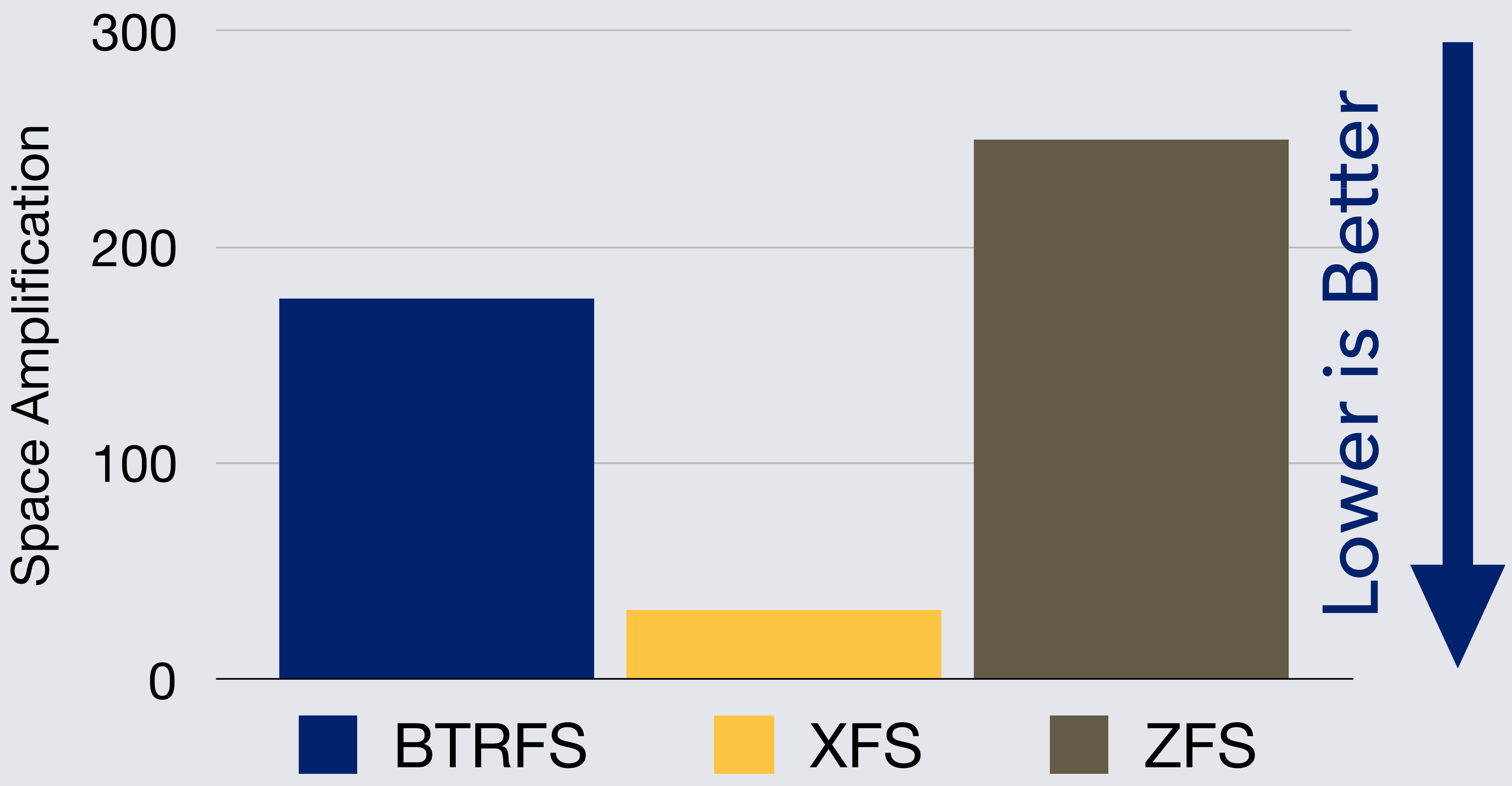

Space Amplification
additional file system size / added data (1KiB)

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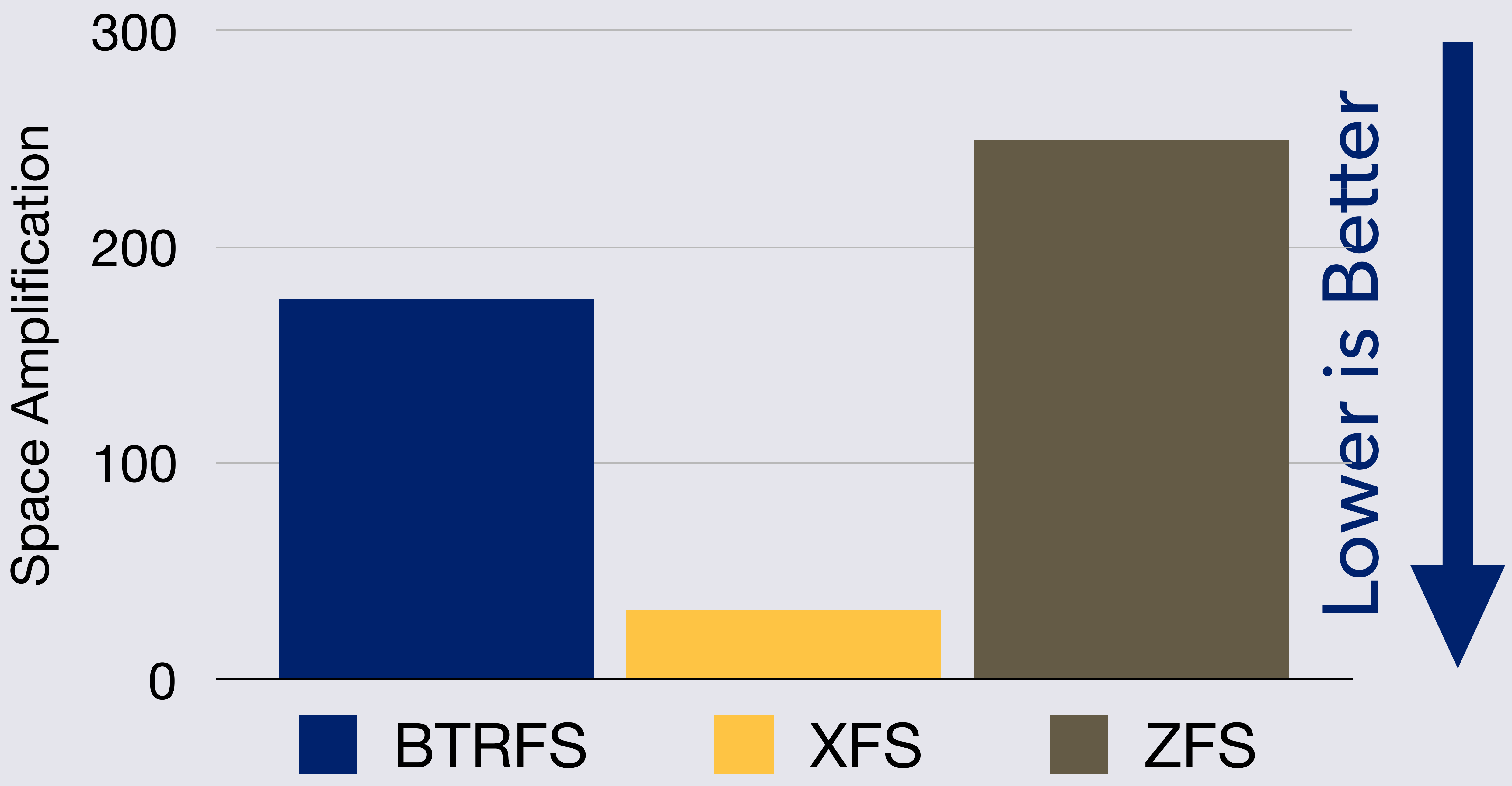

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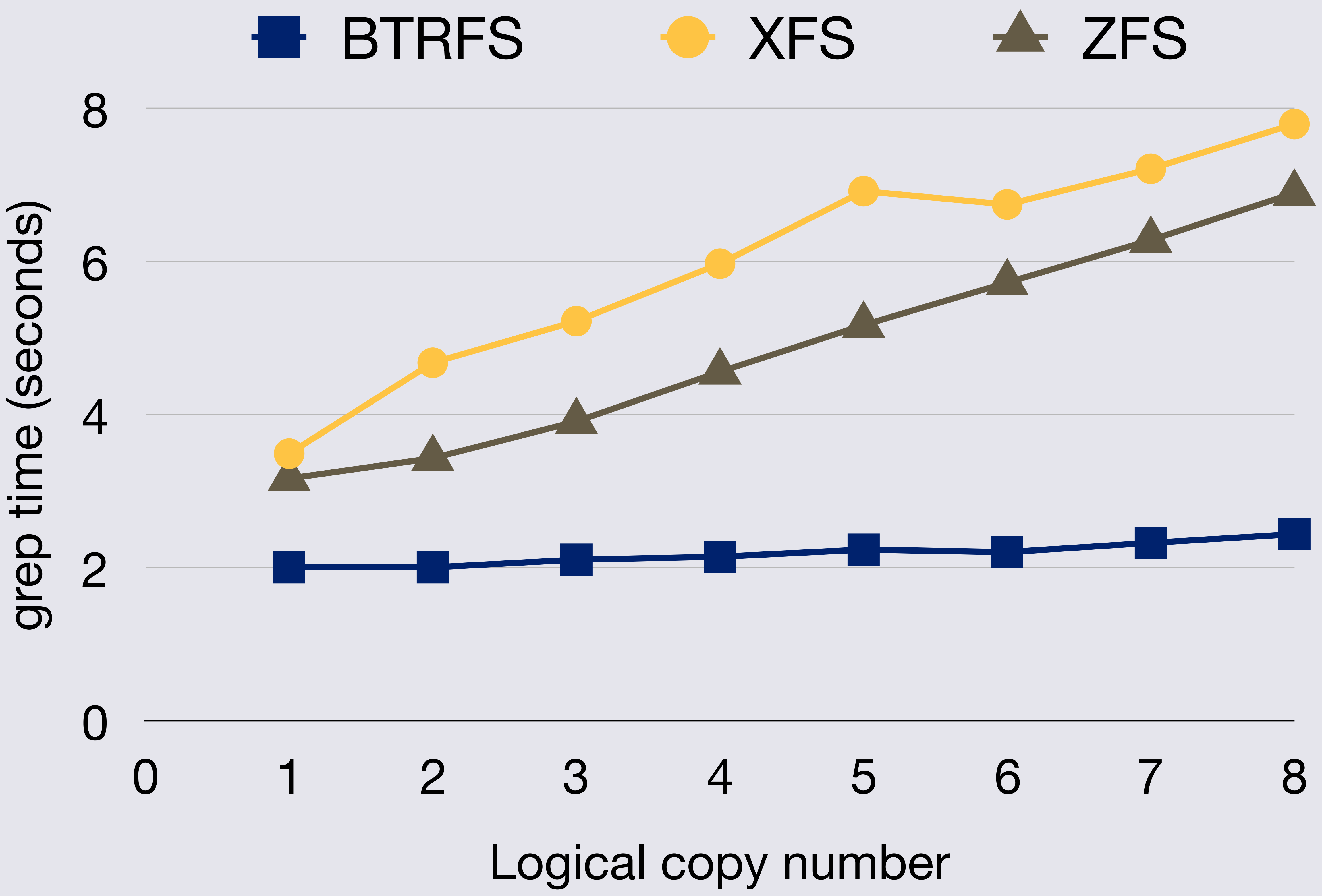

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measured by timing a grep over the latest copy

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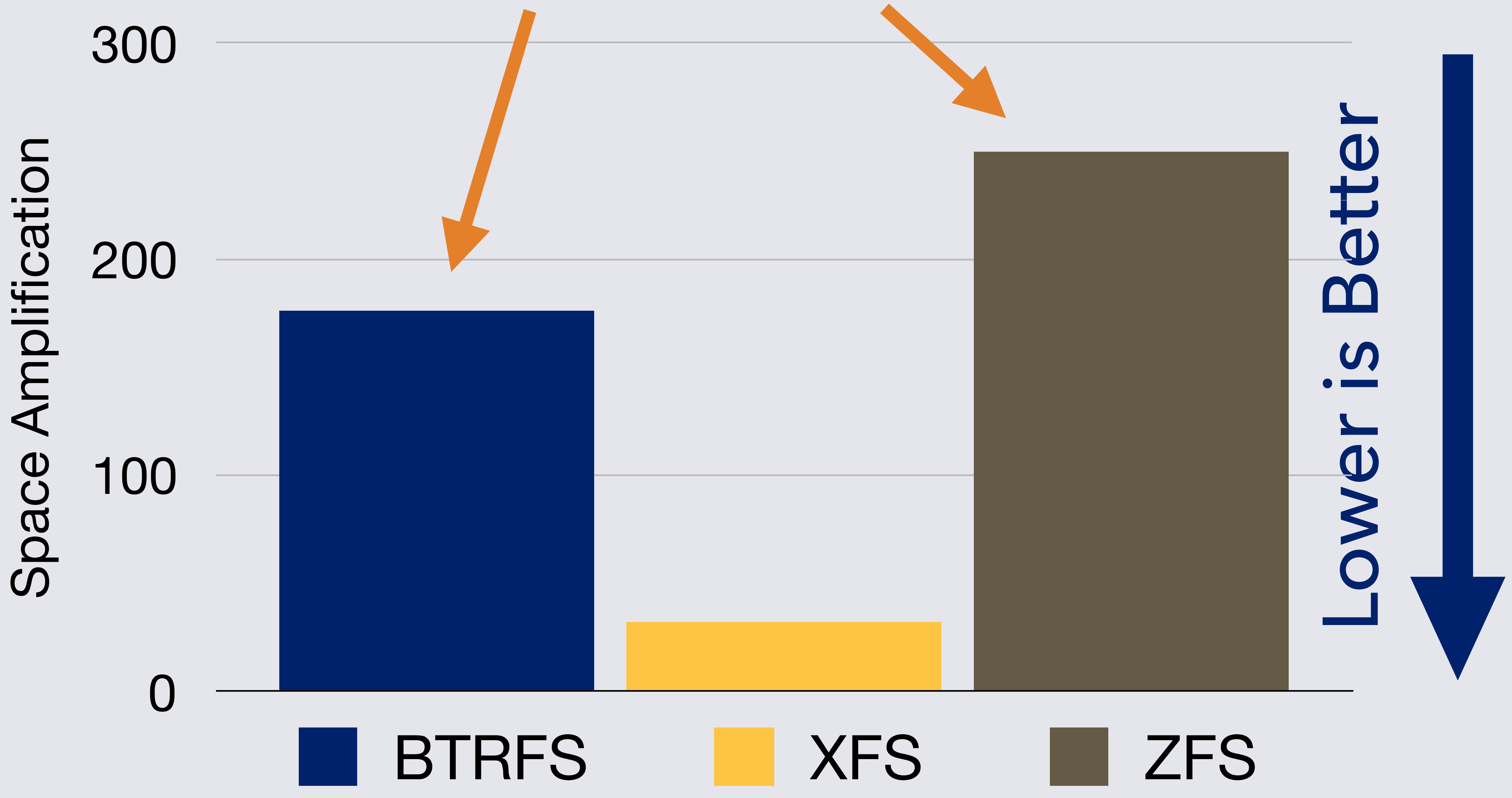
Have large space amplification



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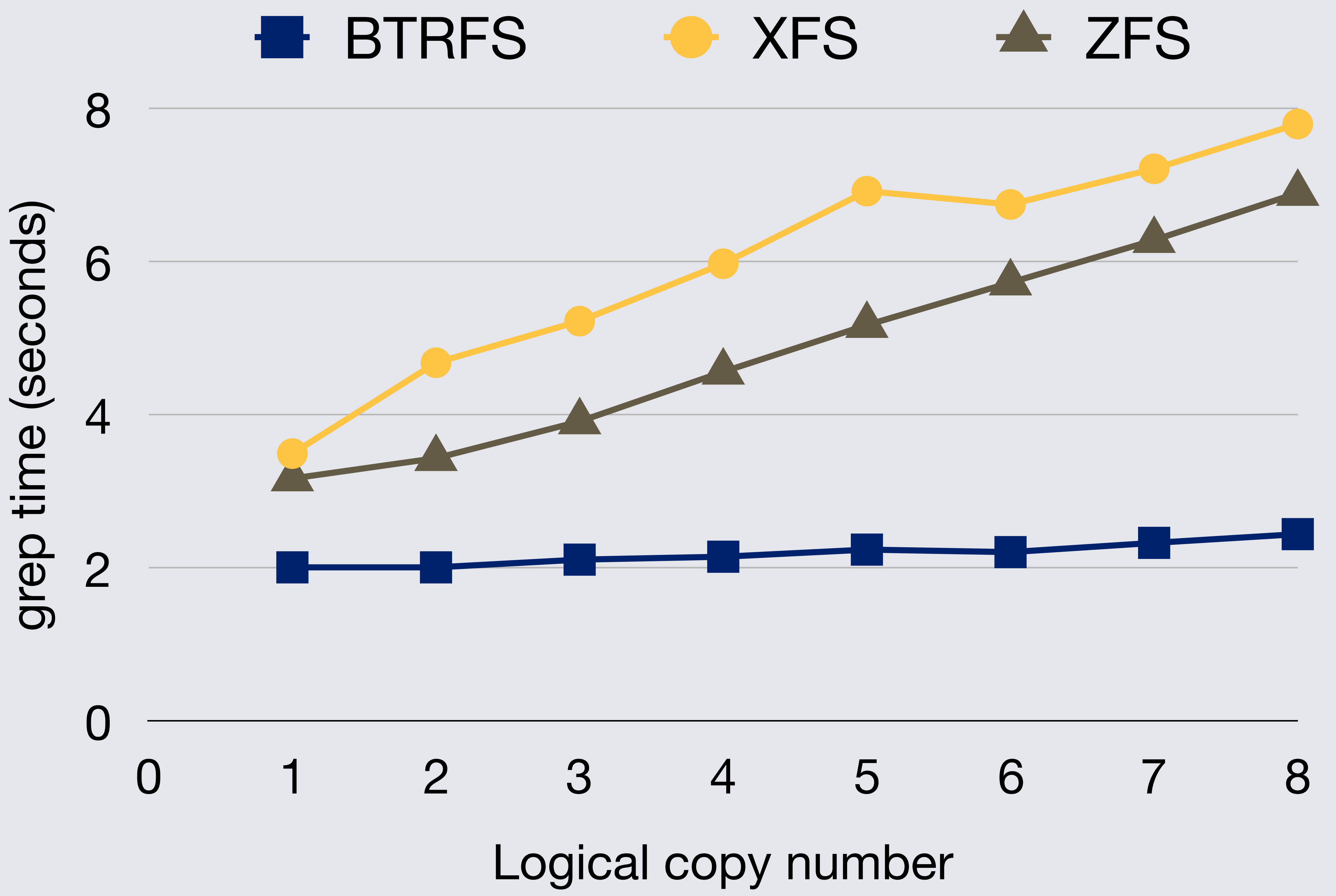

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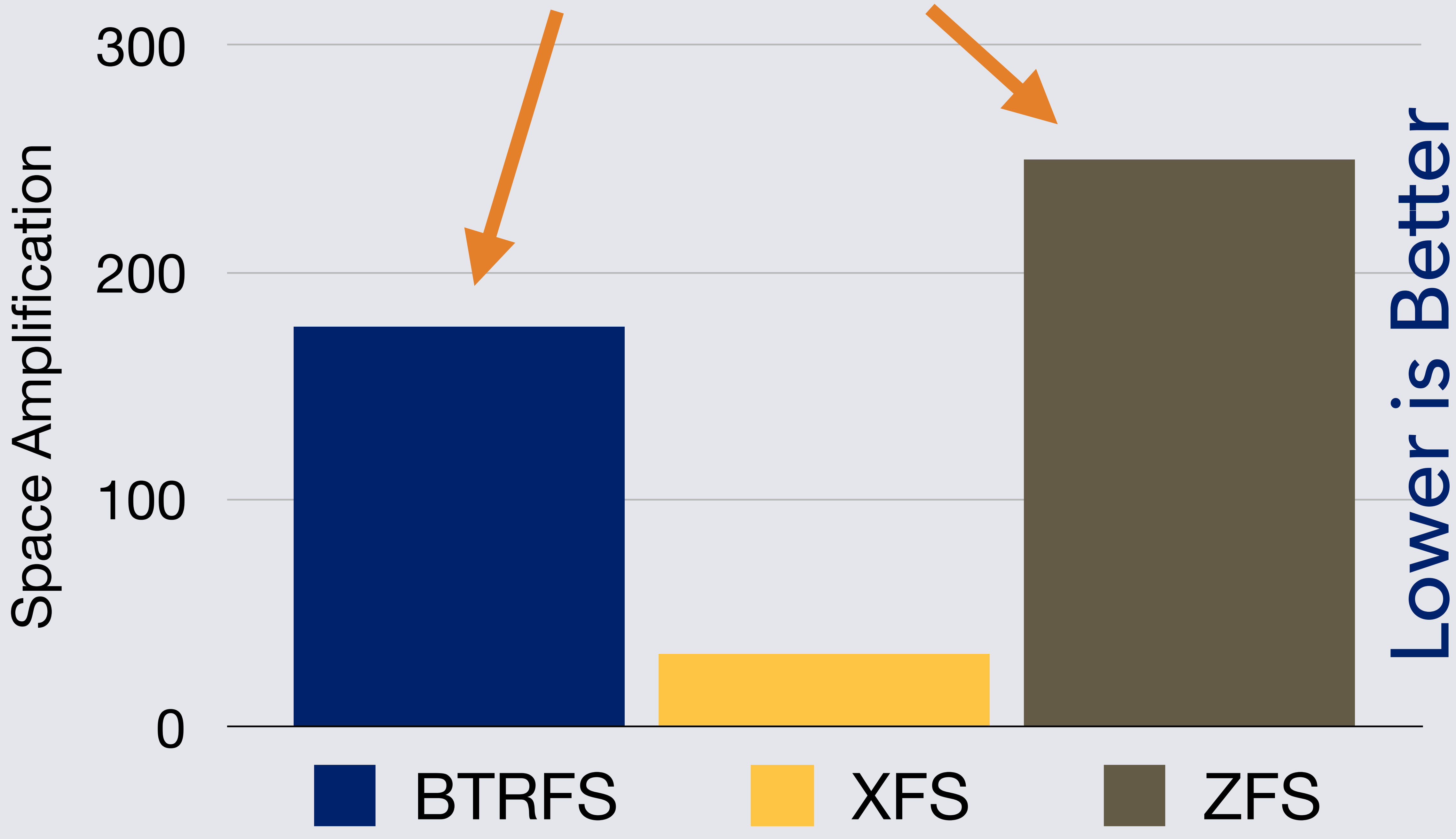
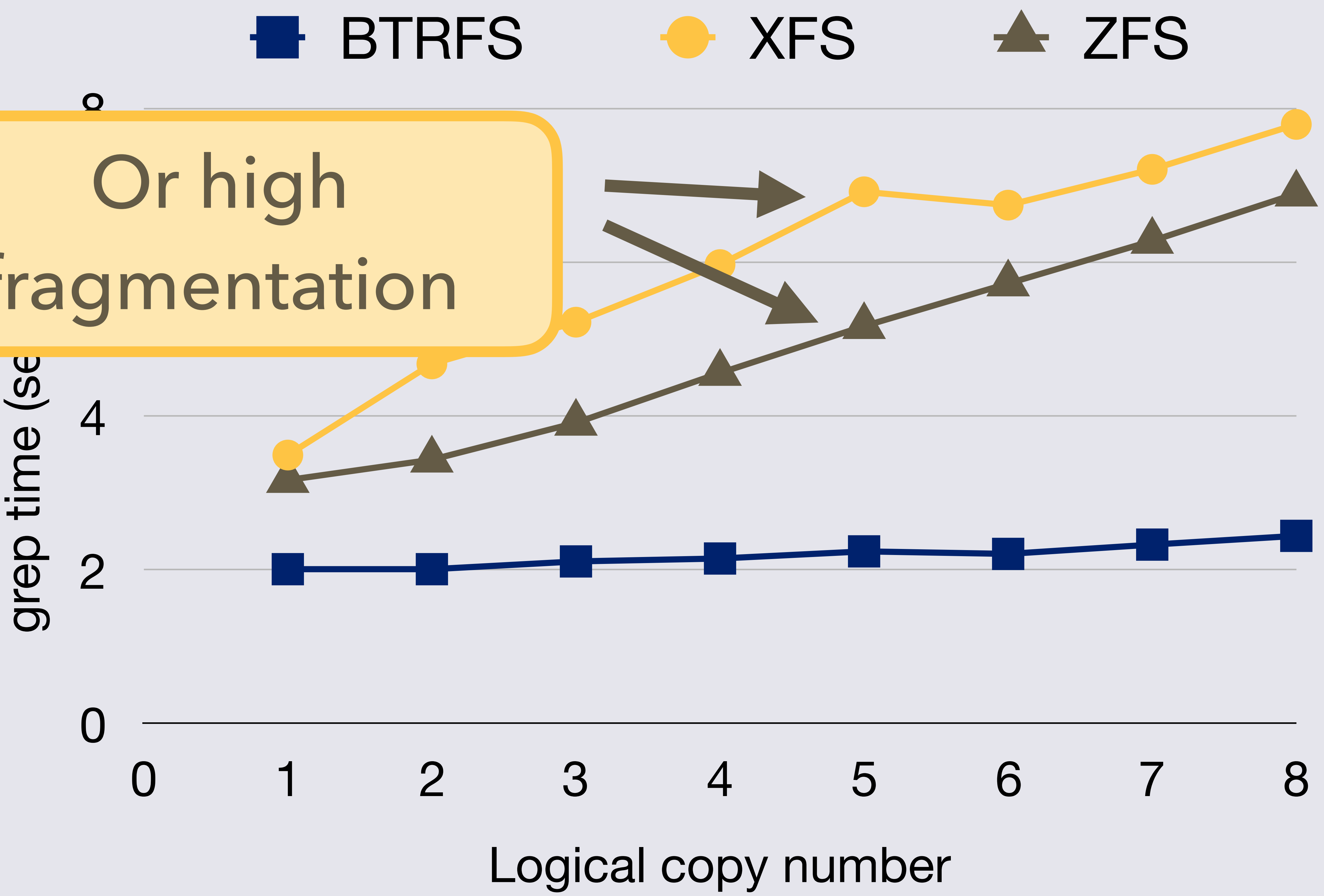


Lower is Better

Or high fragmentation



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Copy Performance Goals

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Space efficient

Low latency

Specific to Copying

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Fast writes

Fast reads

General file system

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Locality

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General file system

Contributions of this Paper

A high performance logical copy implementation…

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Copy-specific	General file system
Space efficient	Fast writes
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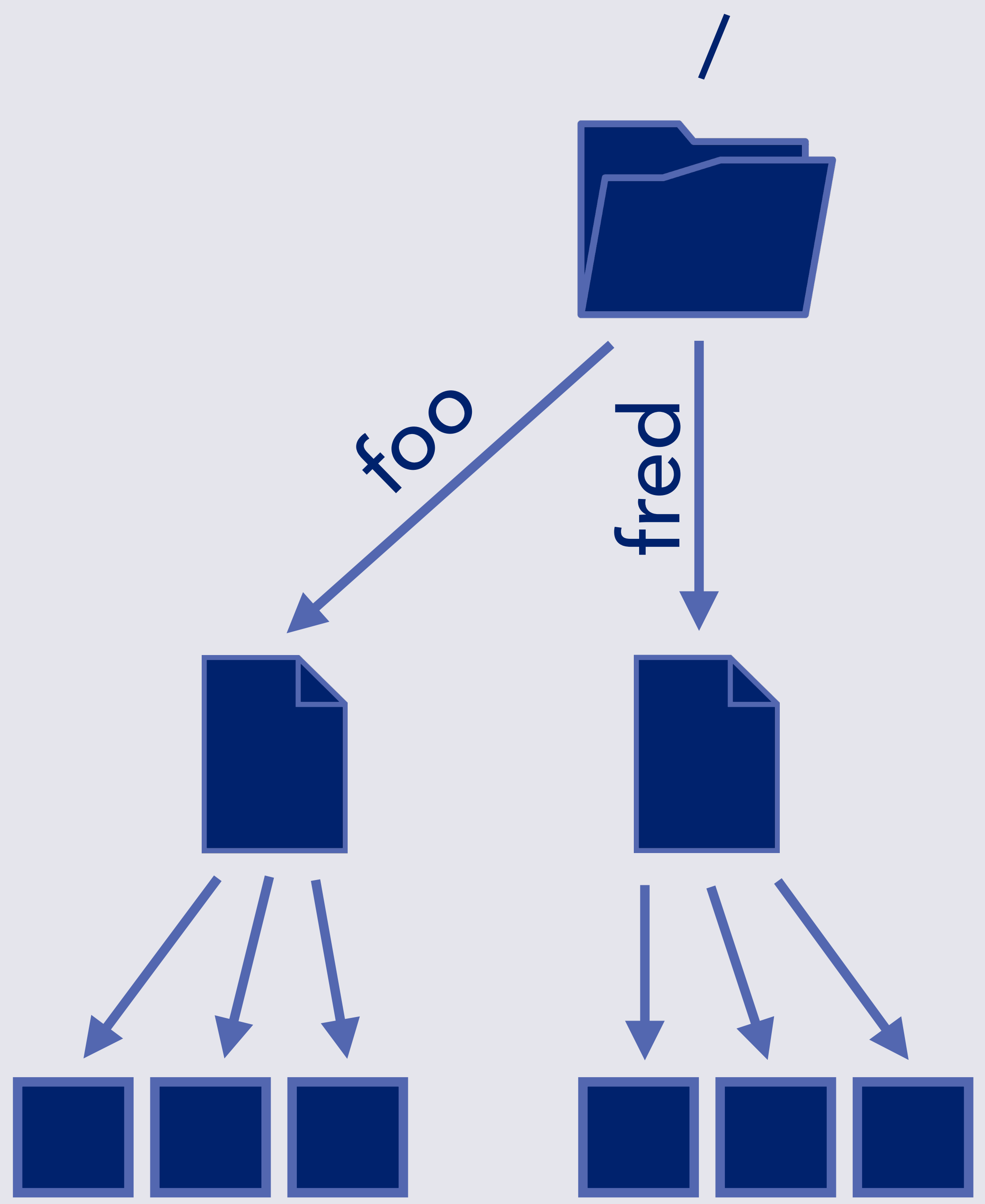
Copy-specific		General file system	
Space efficient	✓	Fast writes	✓
Low latency	✓	Fast reads	✓

What is the Challenge of Logical Copy?

Example: Logical copy in an inode file system

Logical Copy in an Inode File System

Copy /foo to /bar



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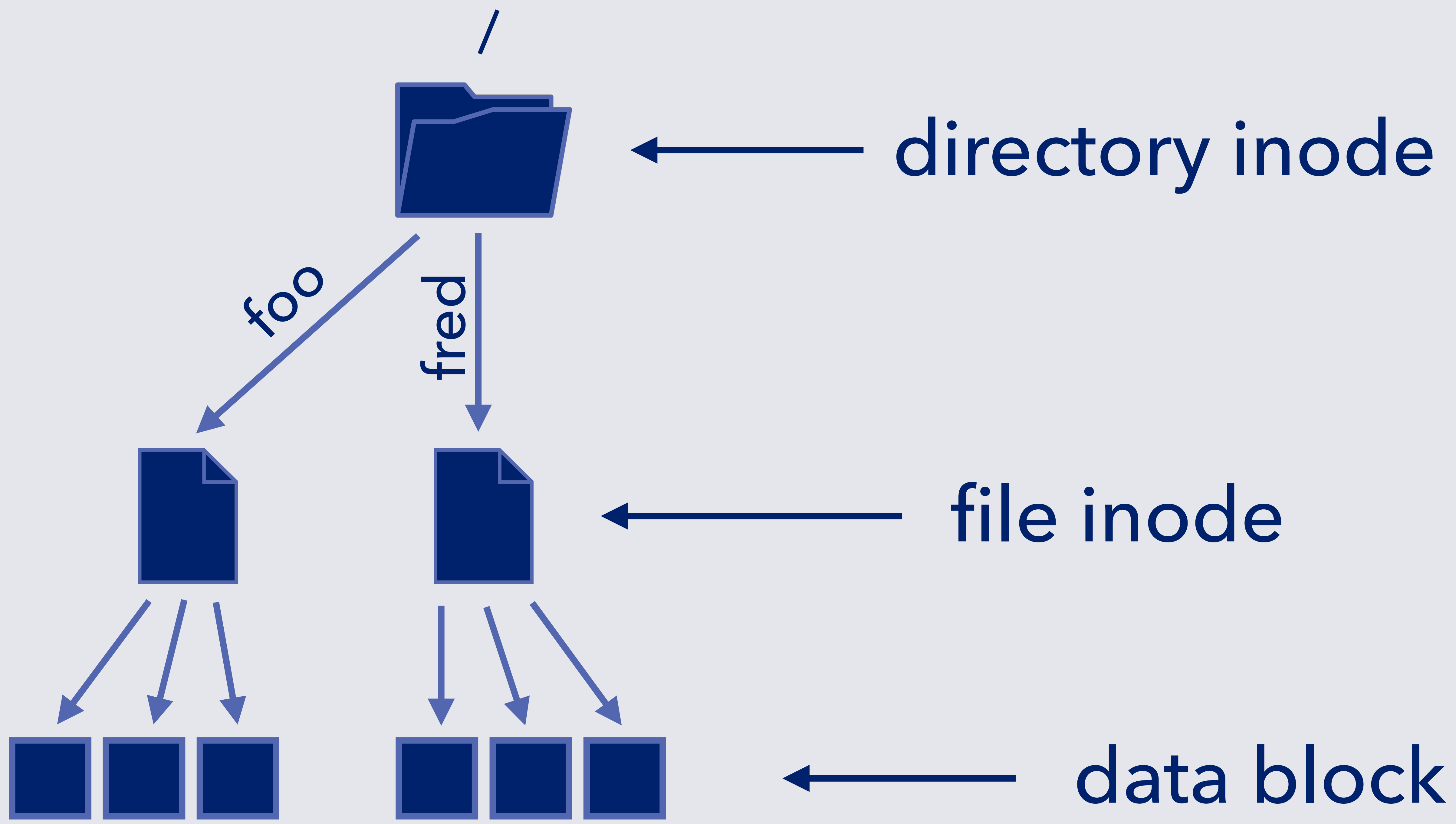

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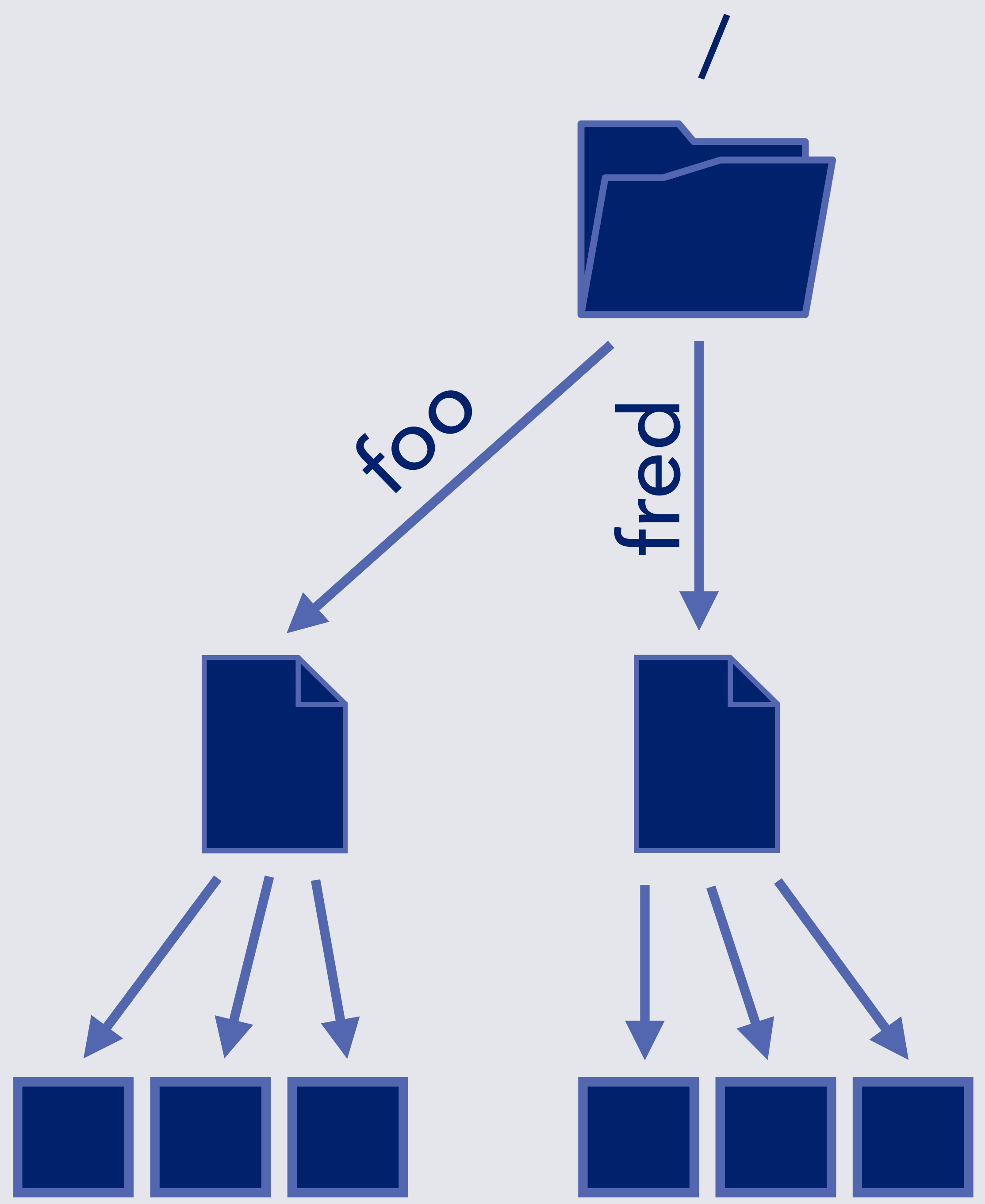

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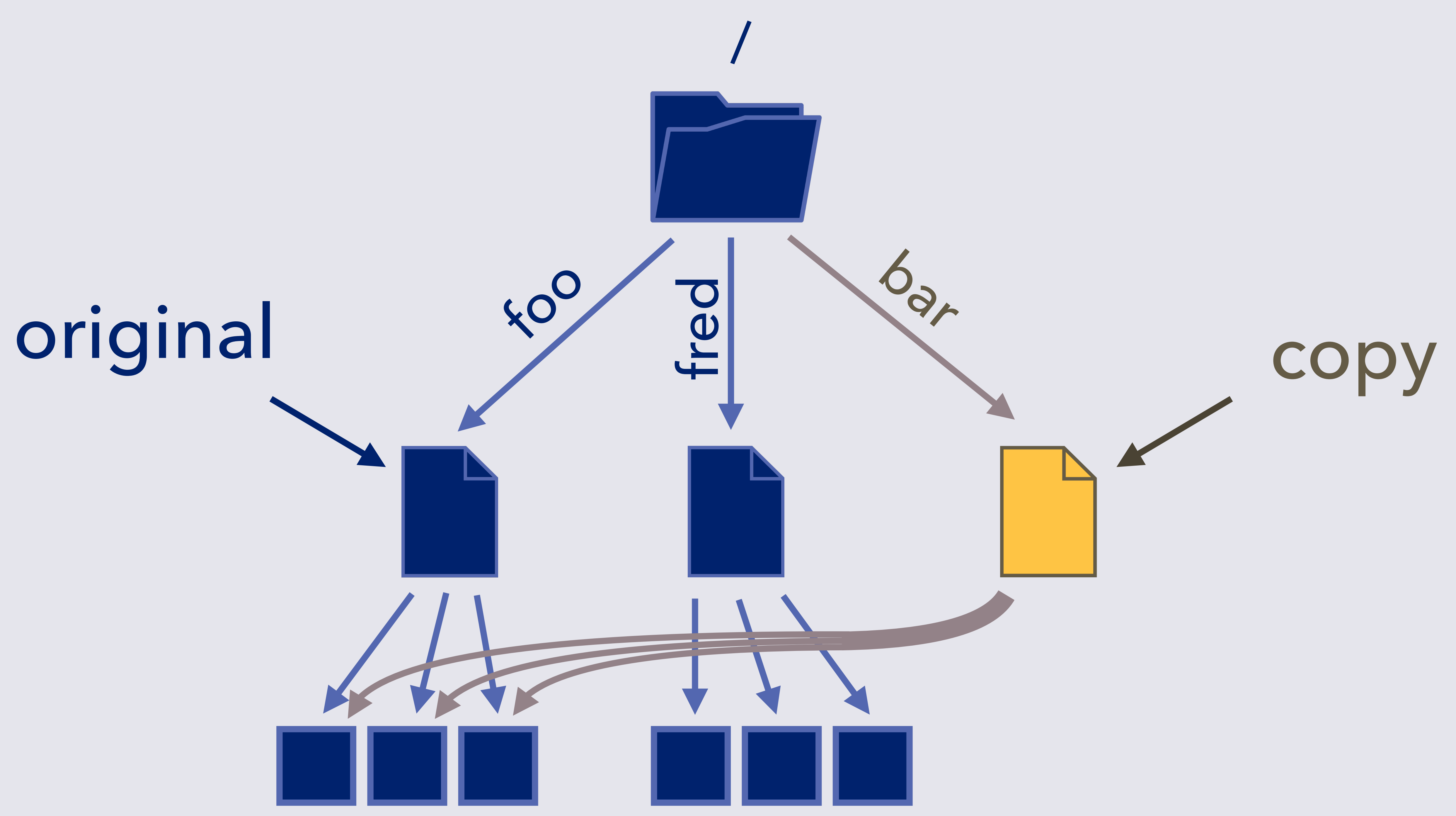

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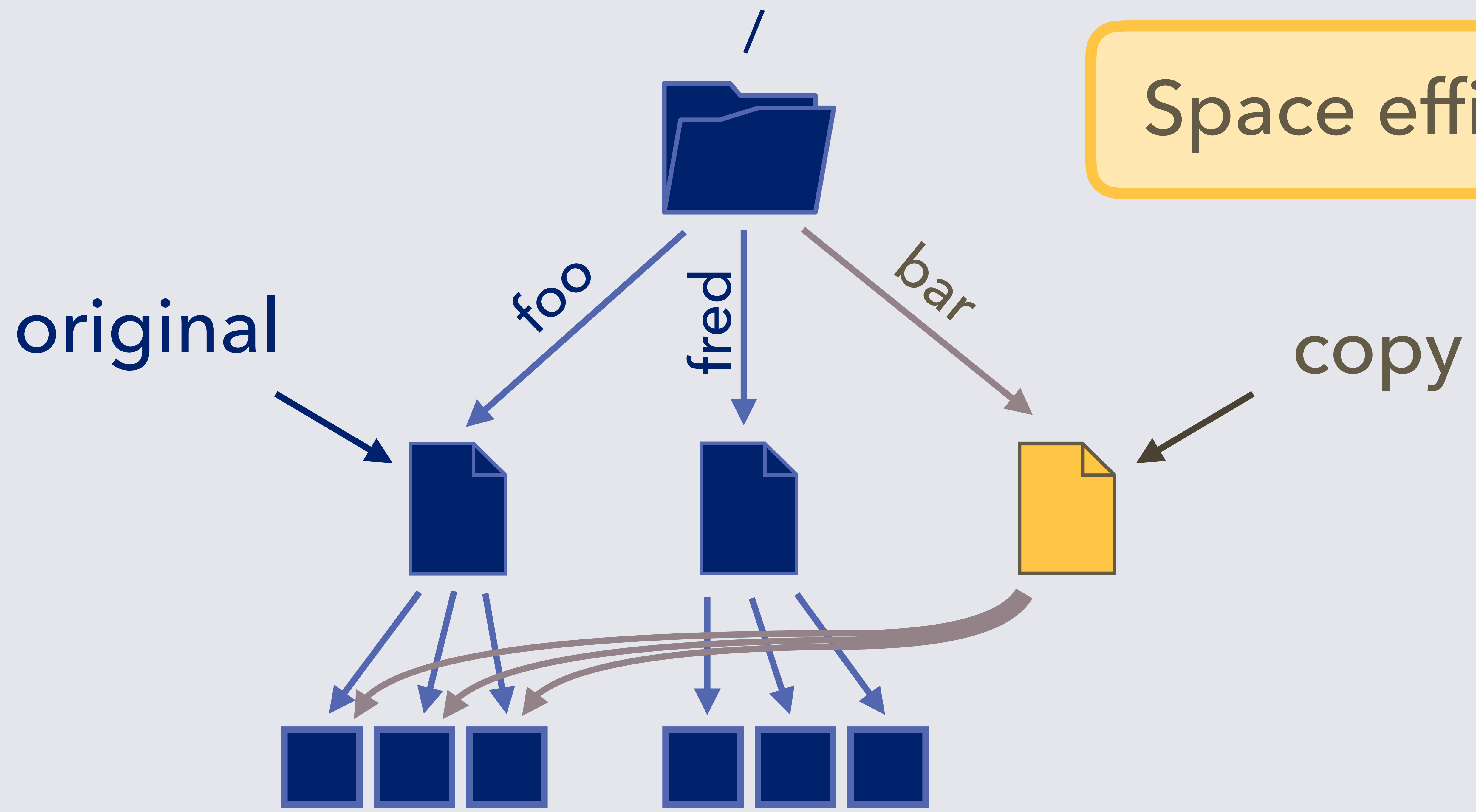
Fast Reads ?

Fast Writes ?



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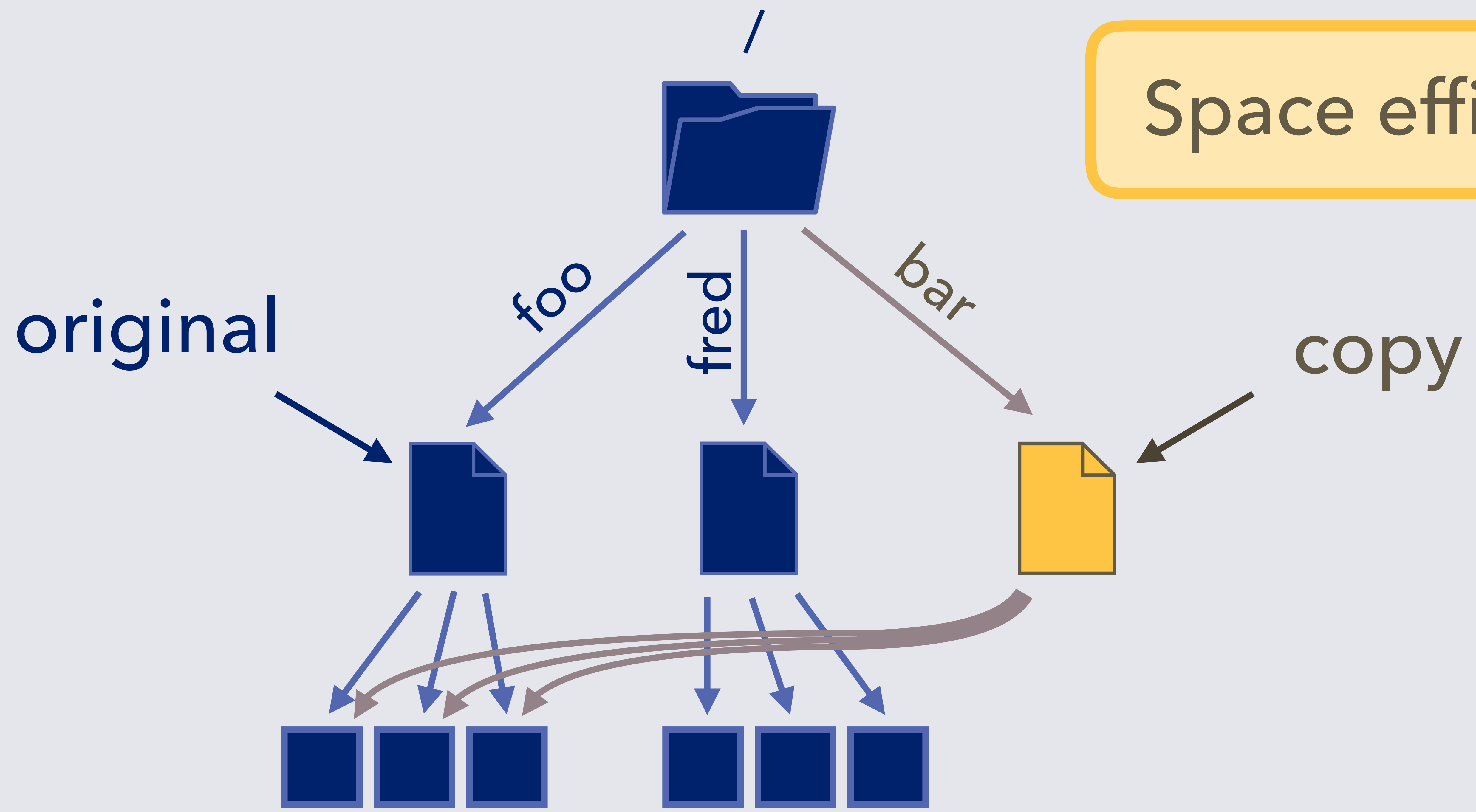

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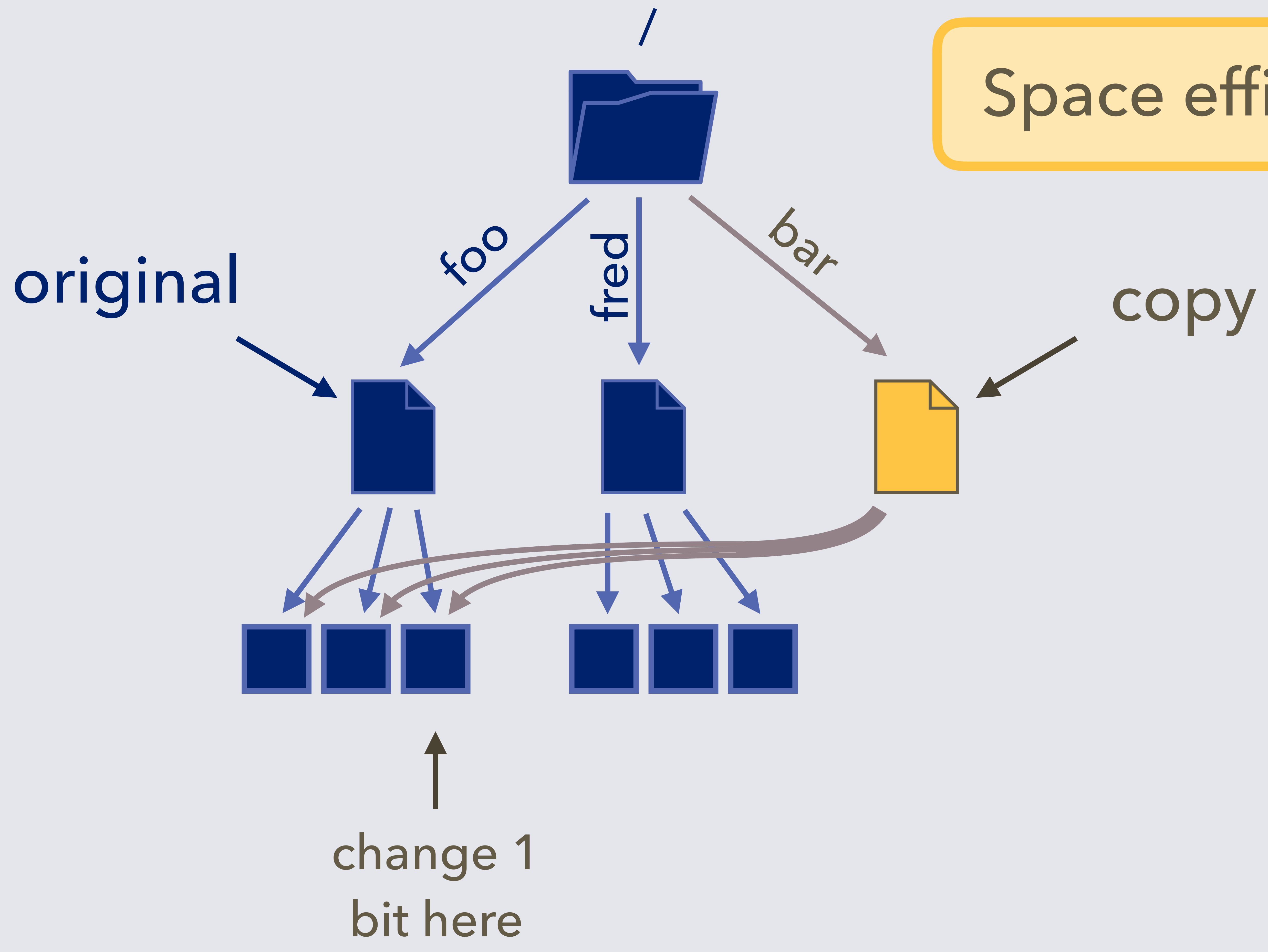

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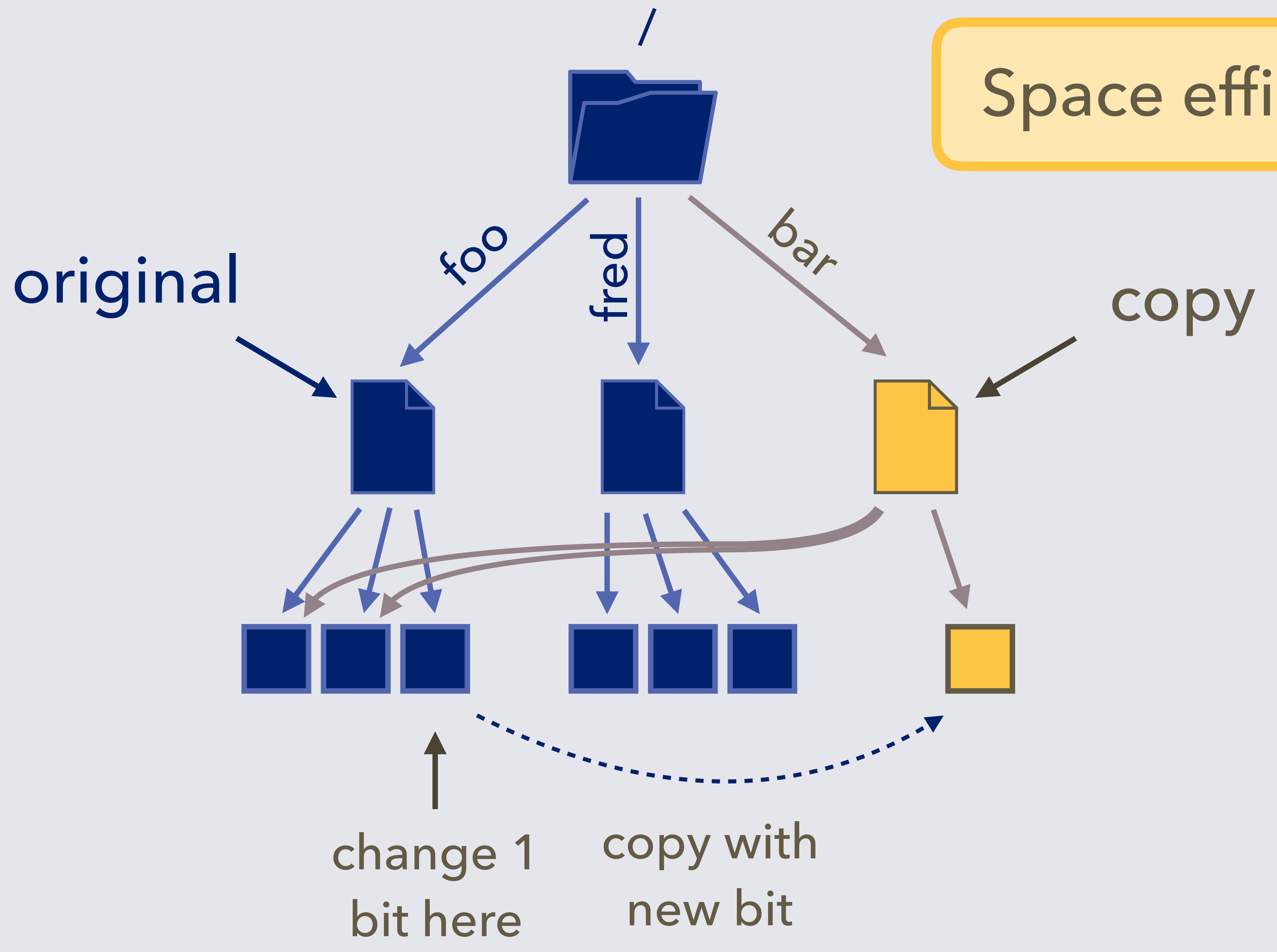

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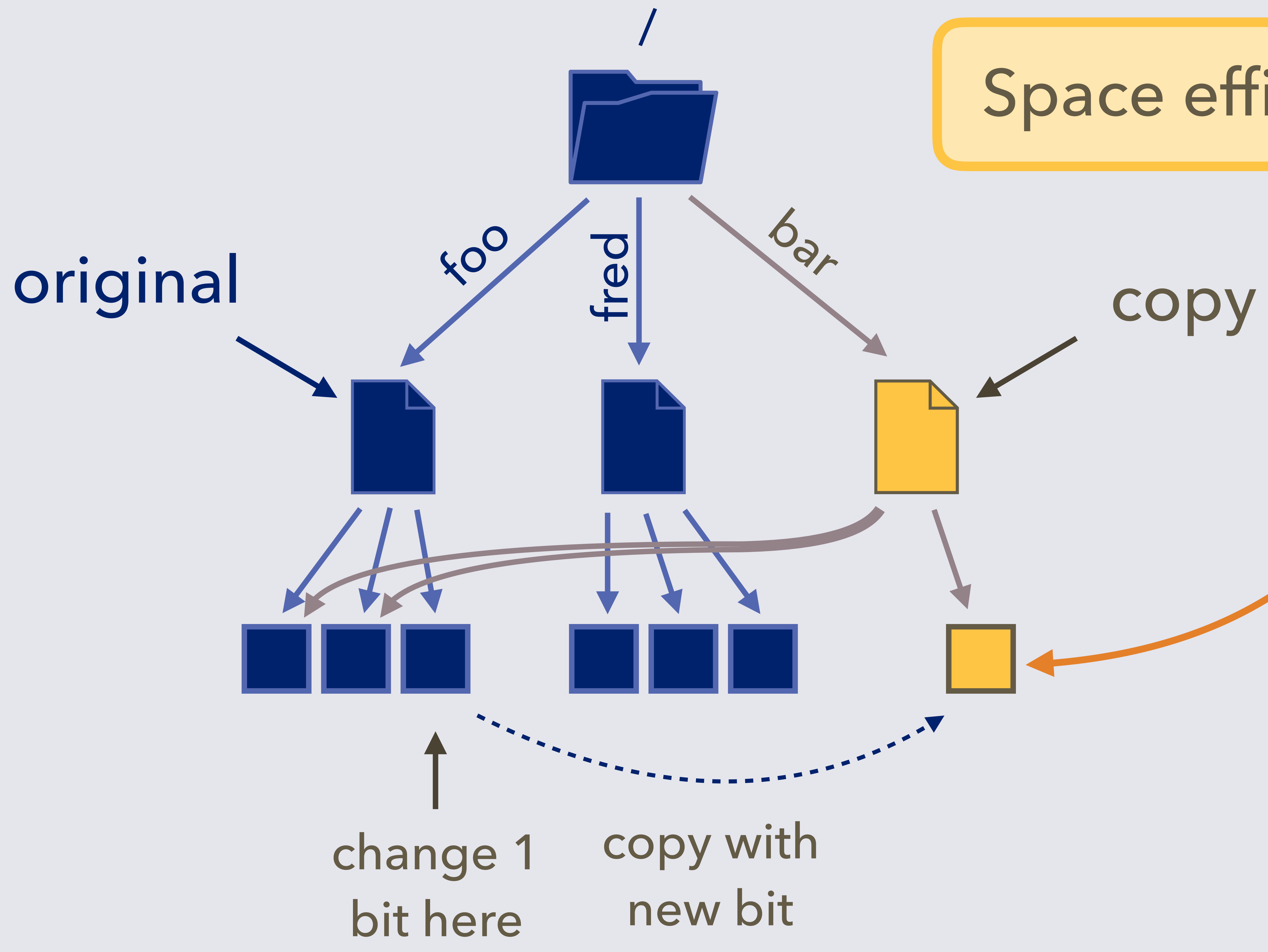

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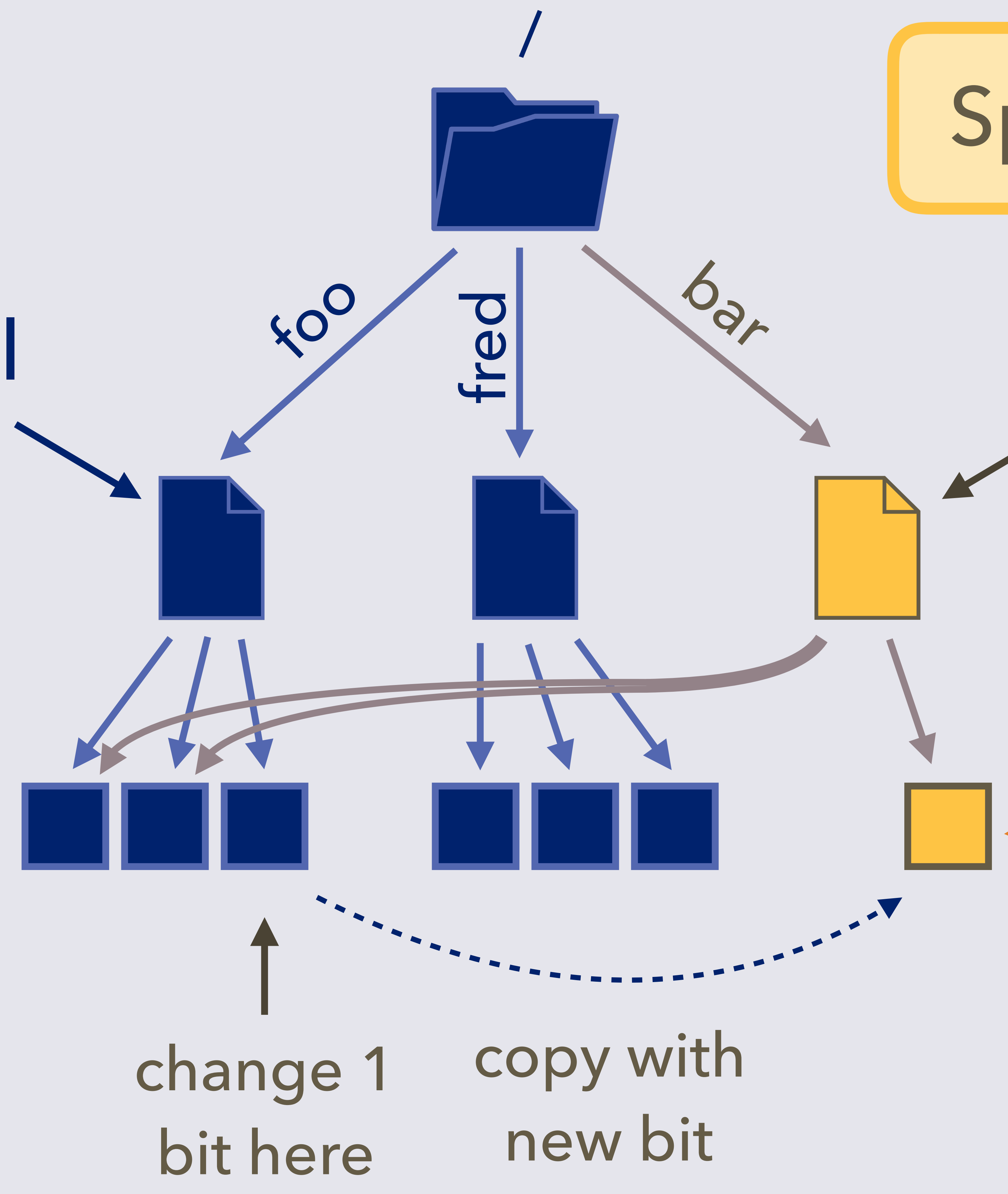

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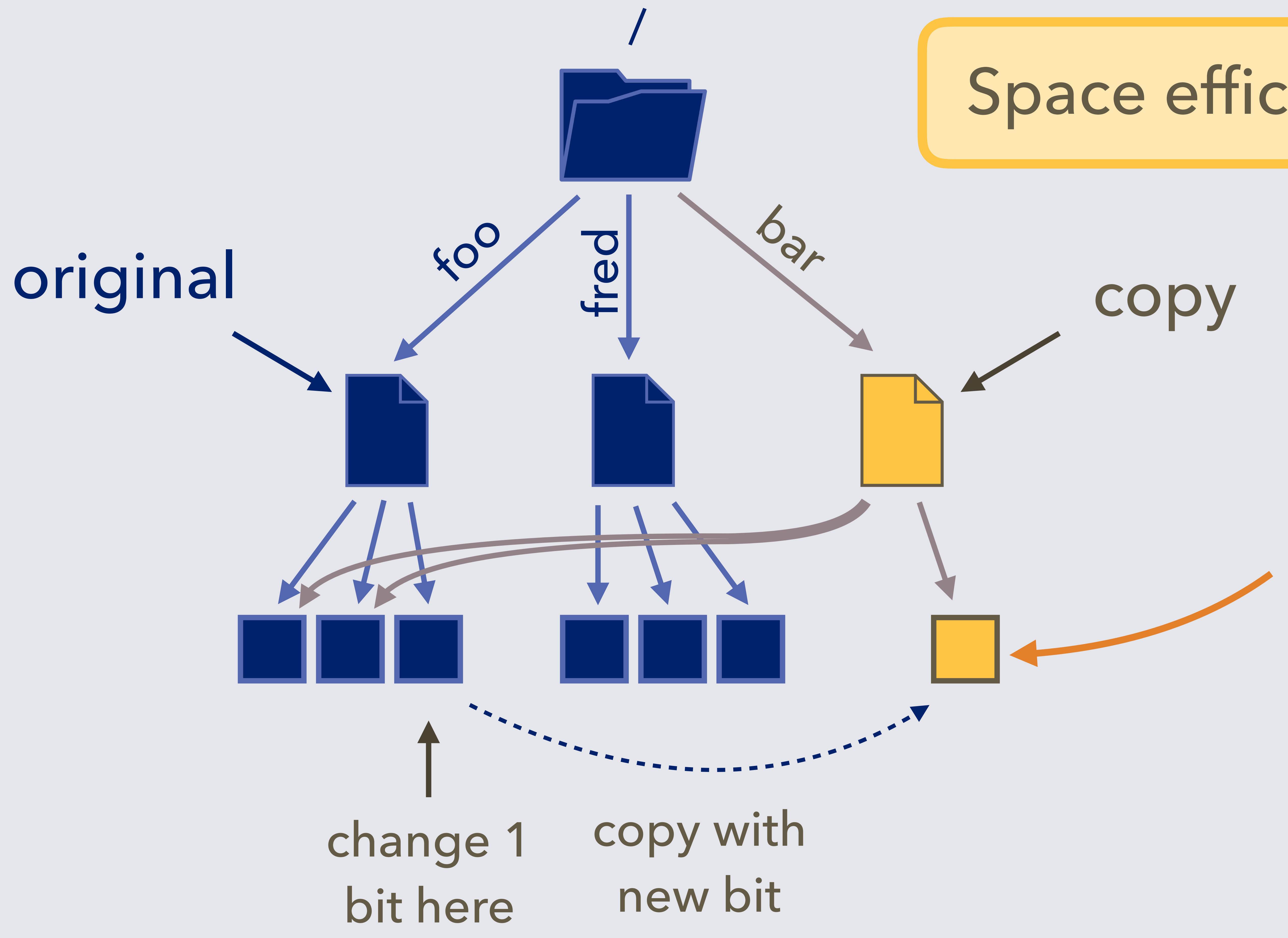

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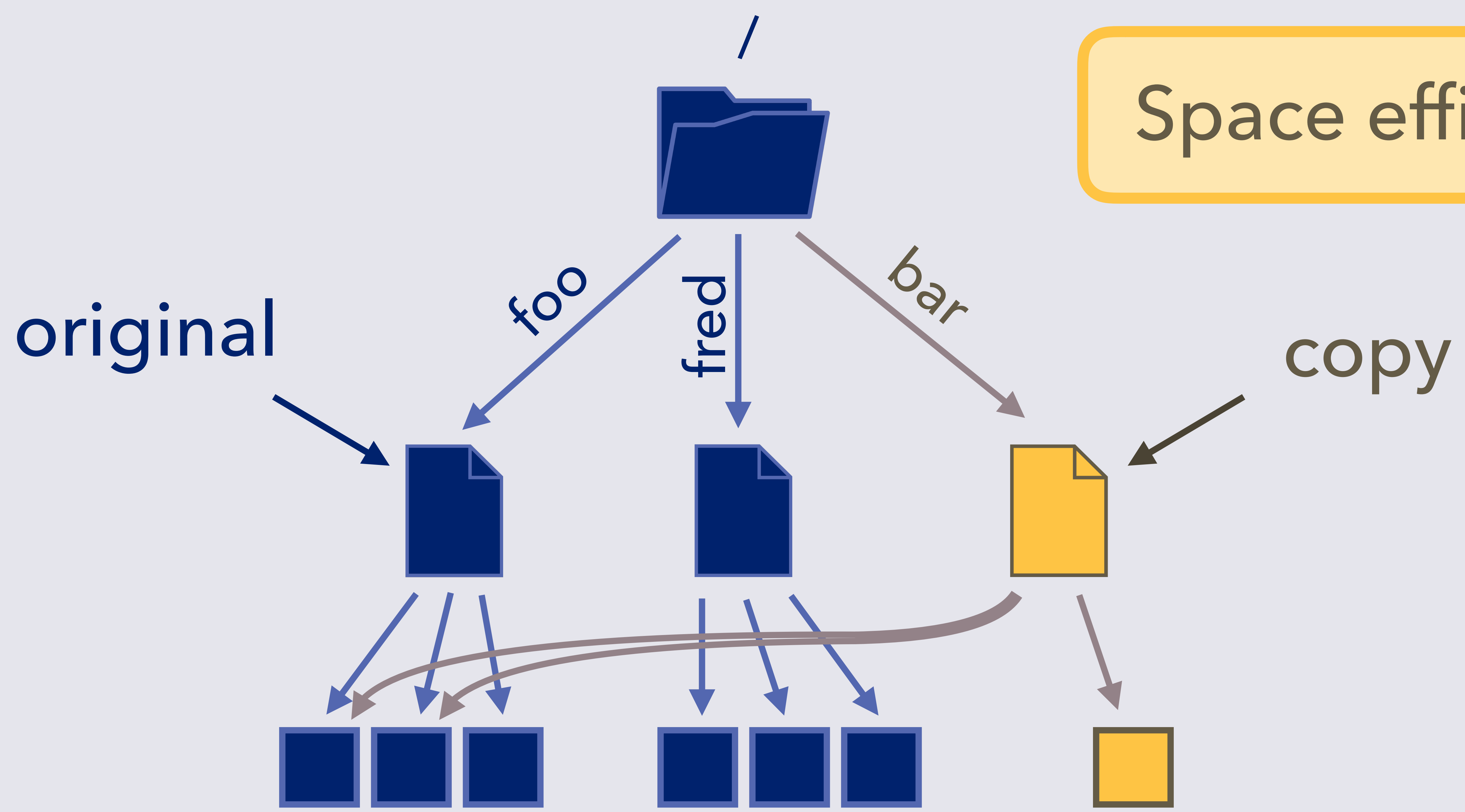

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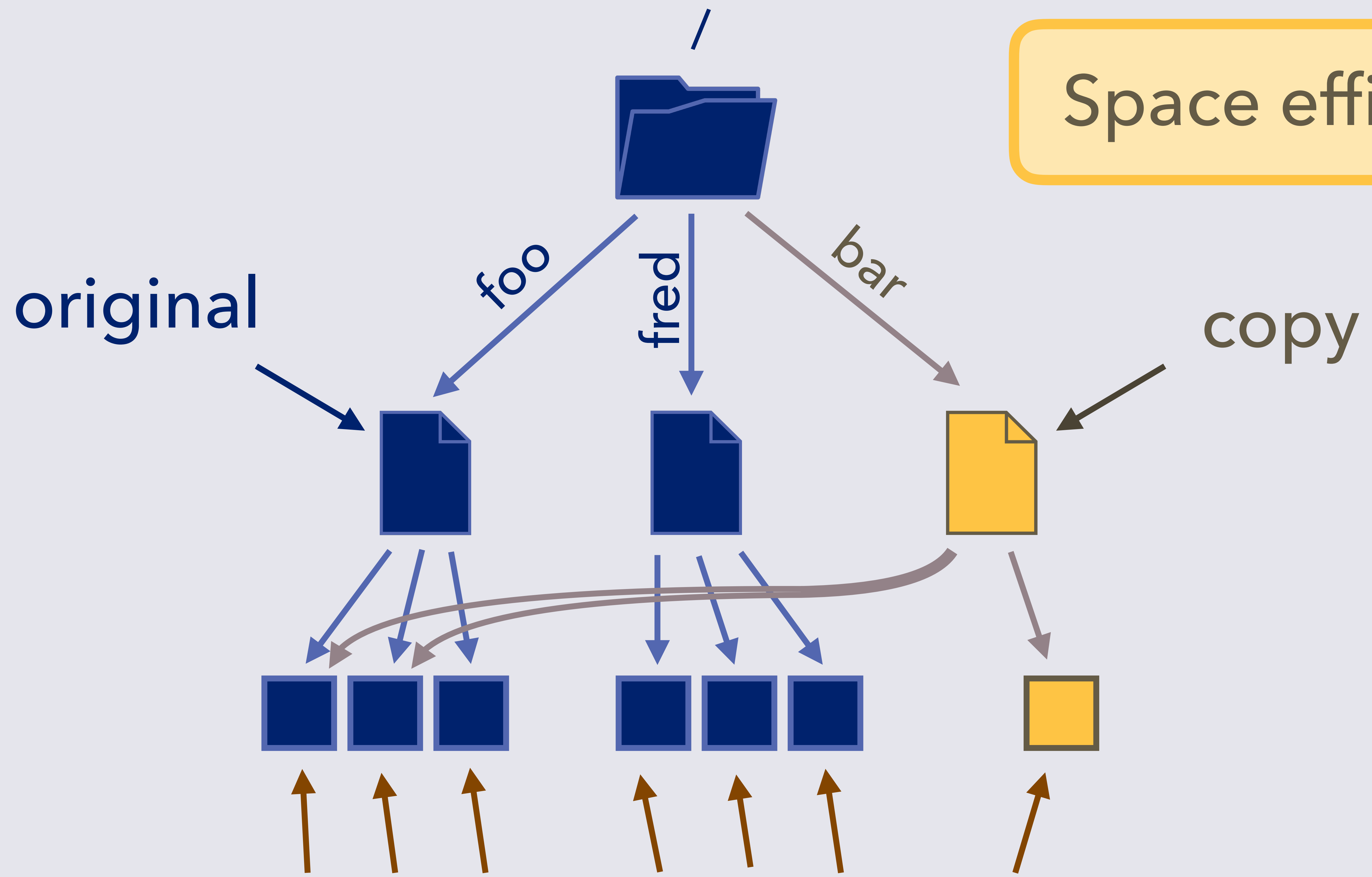

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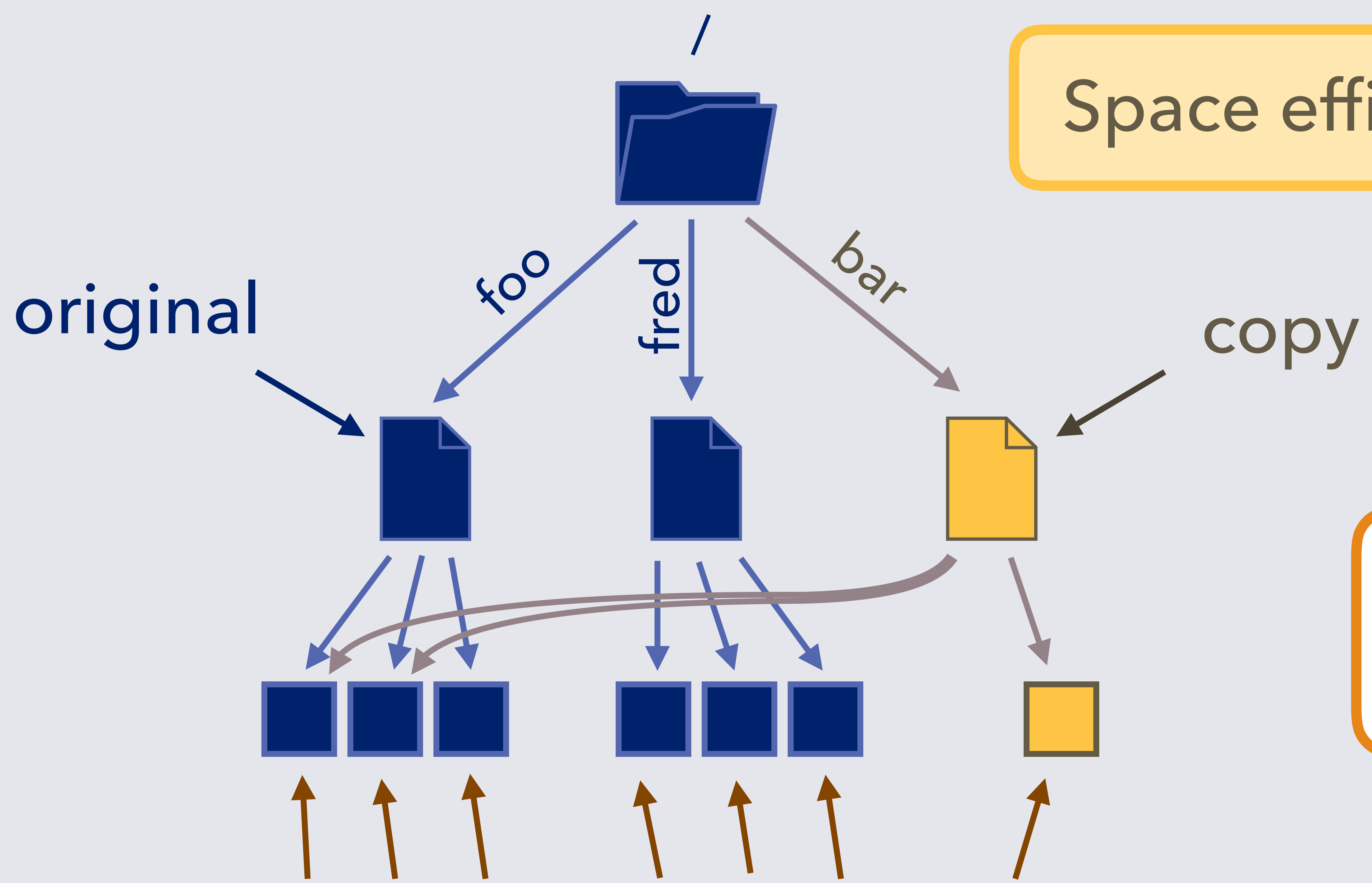

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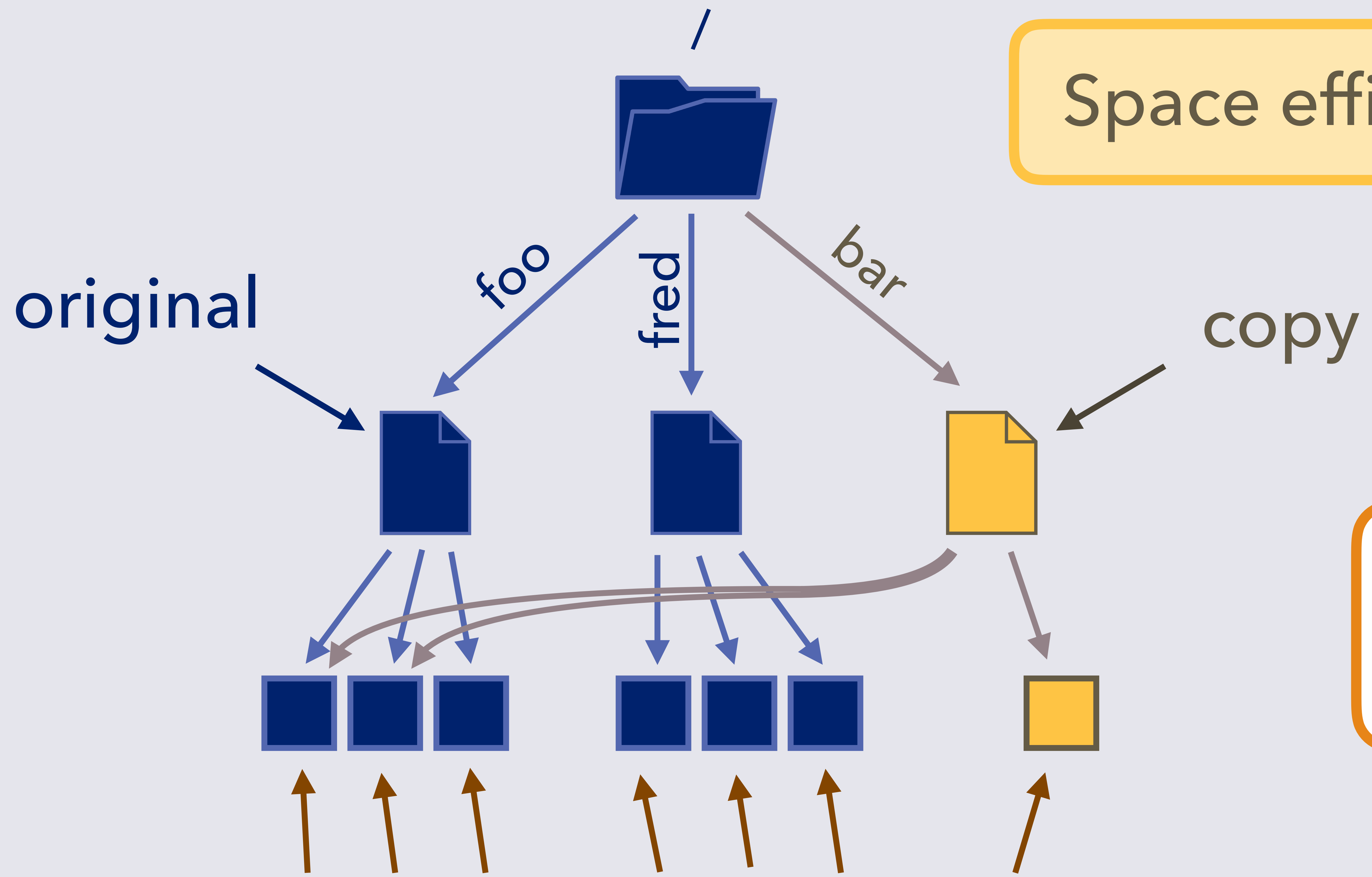

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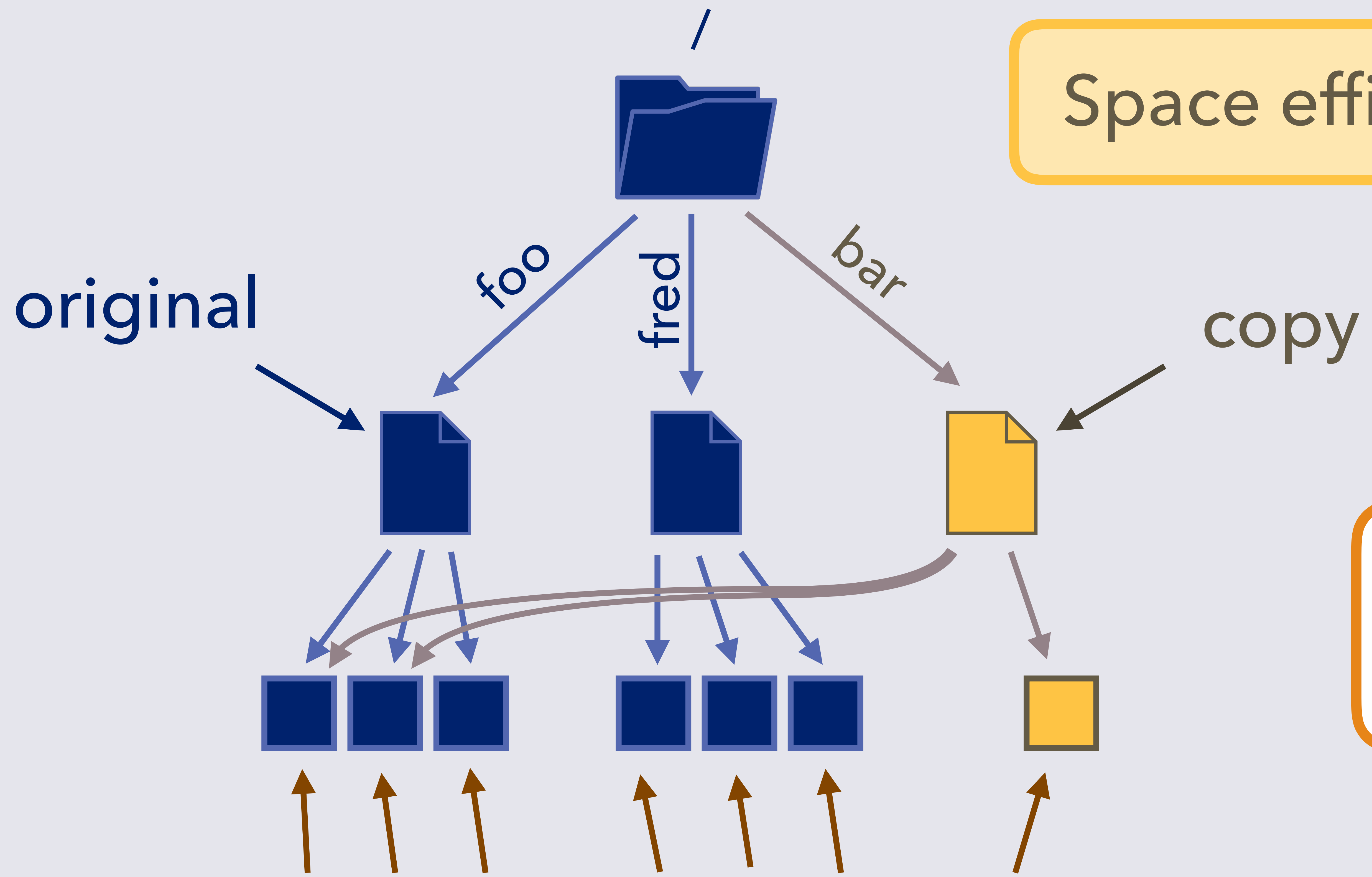

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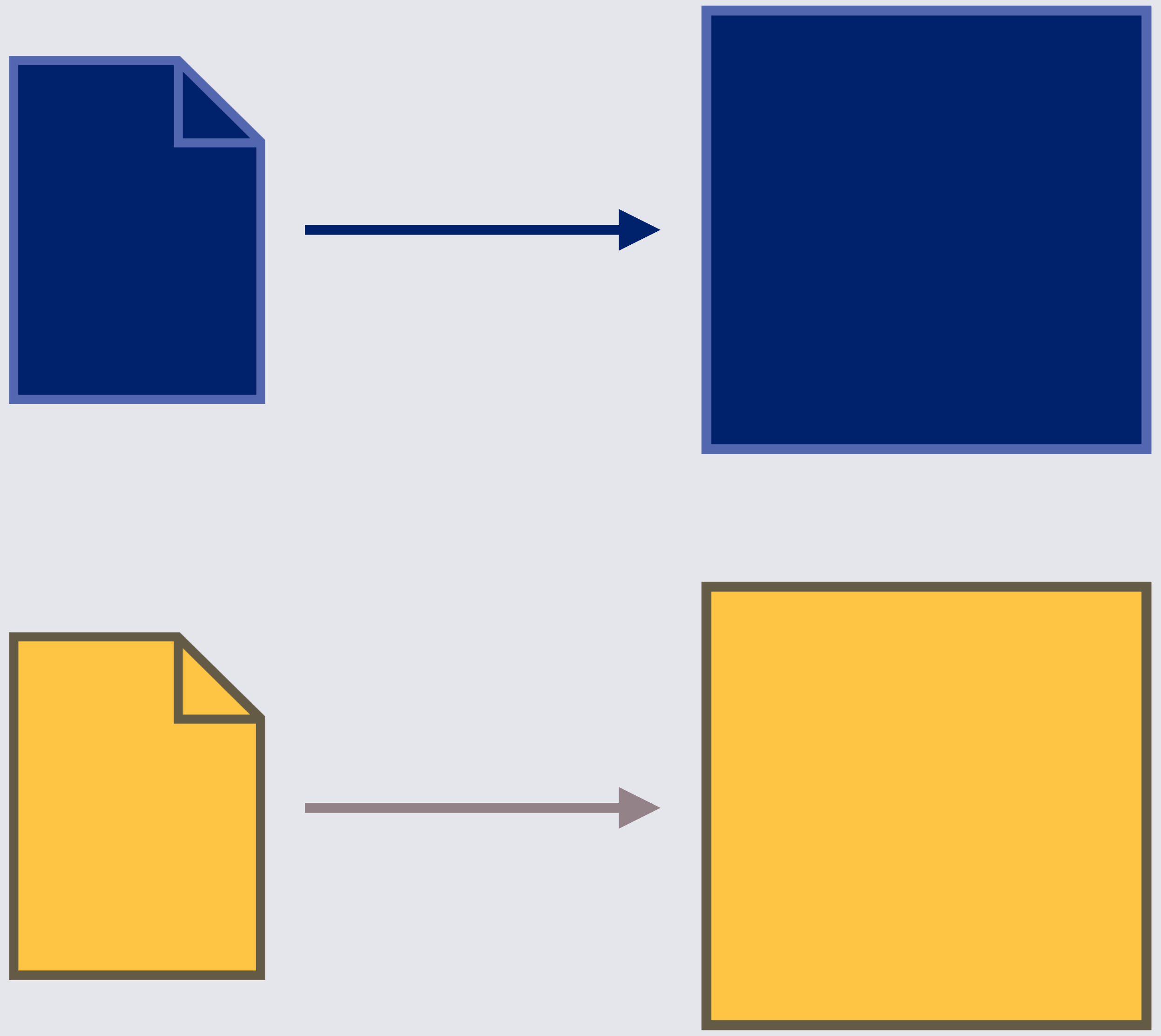
Space-Locality Tradeoff

Larger blocks



Better locality 😄

Worse space efficiency 😬

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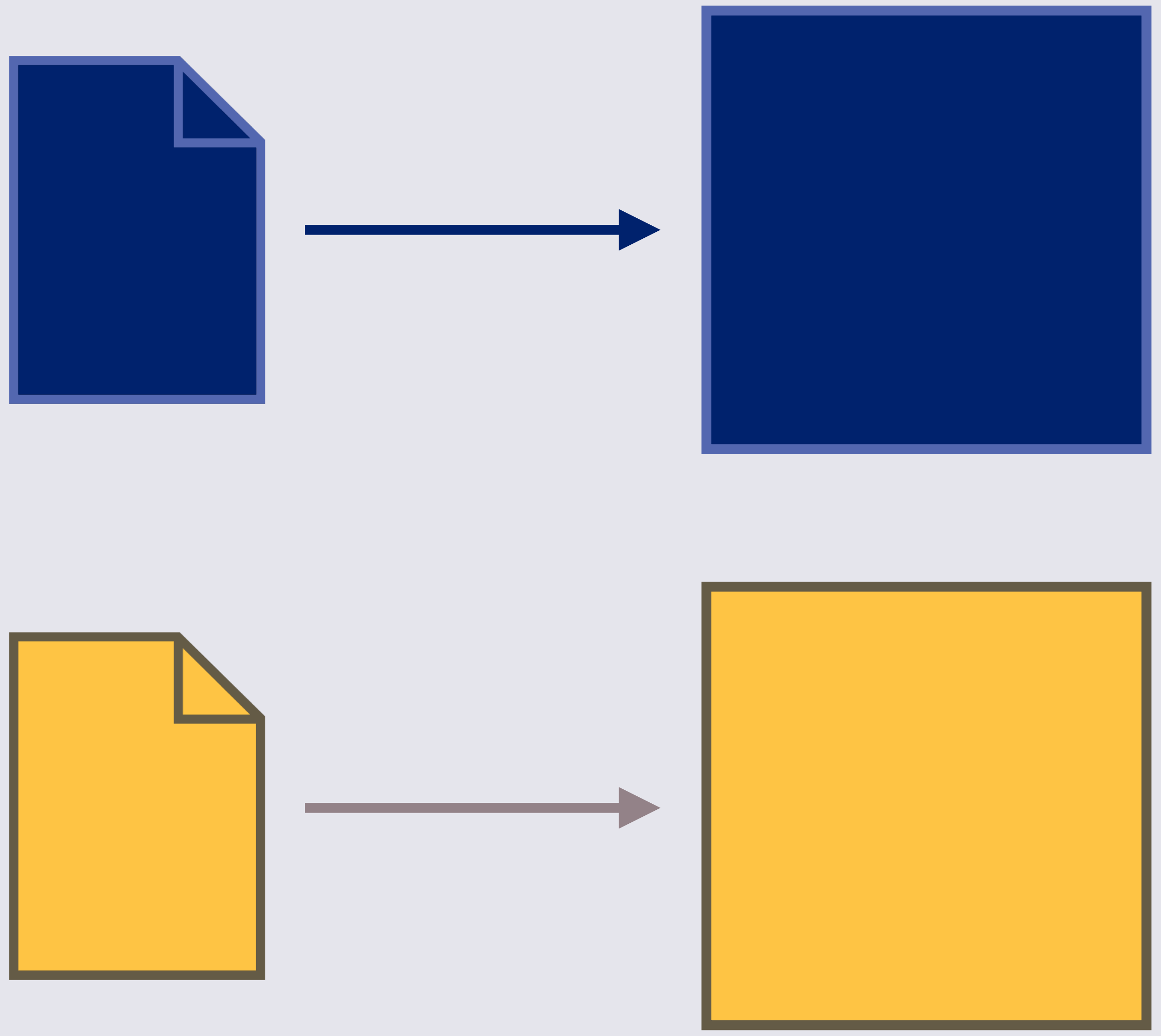

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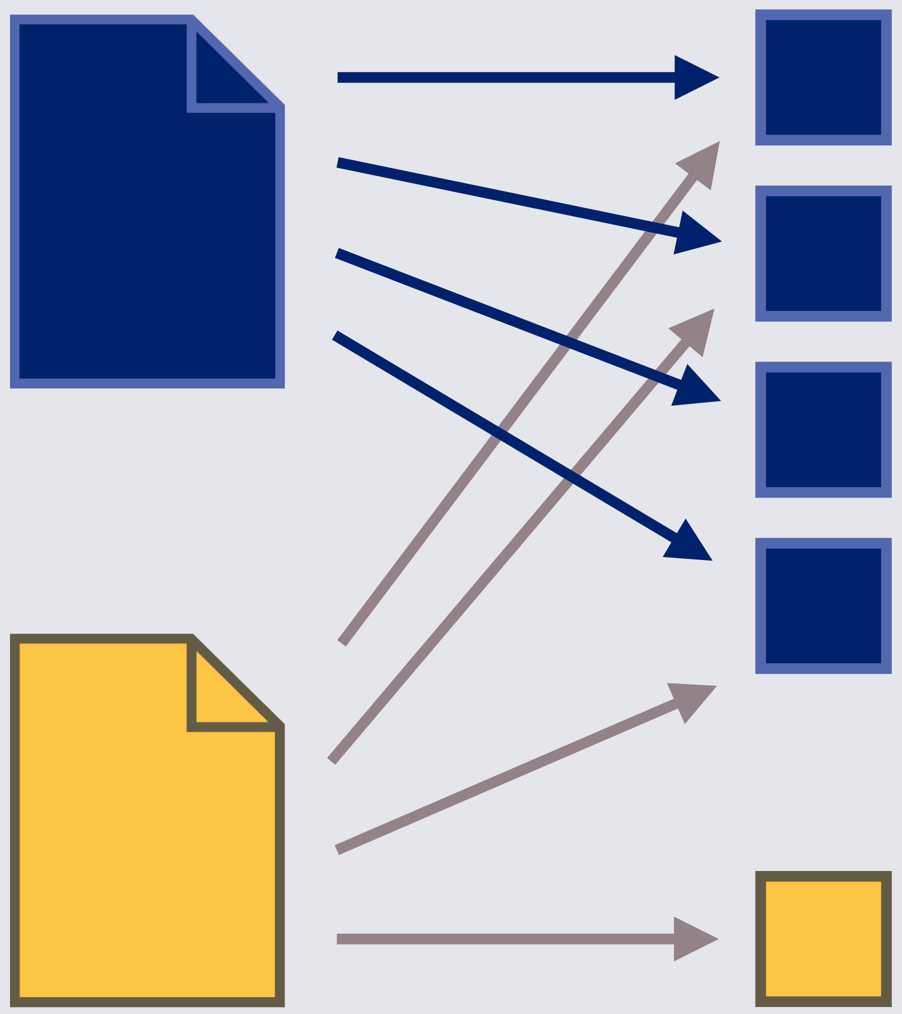

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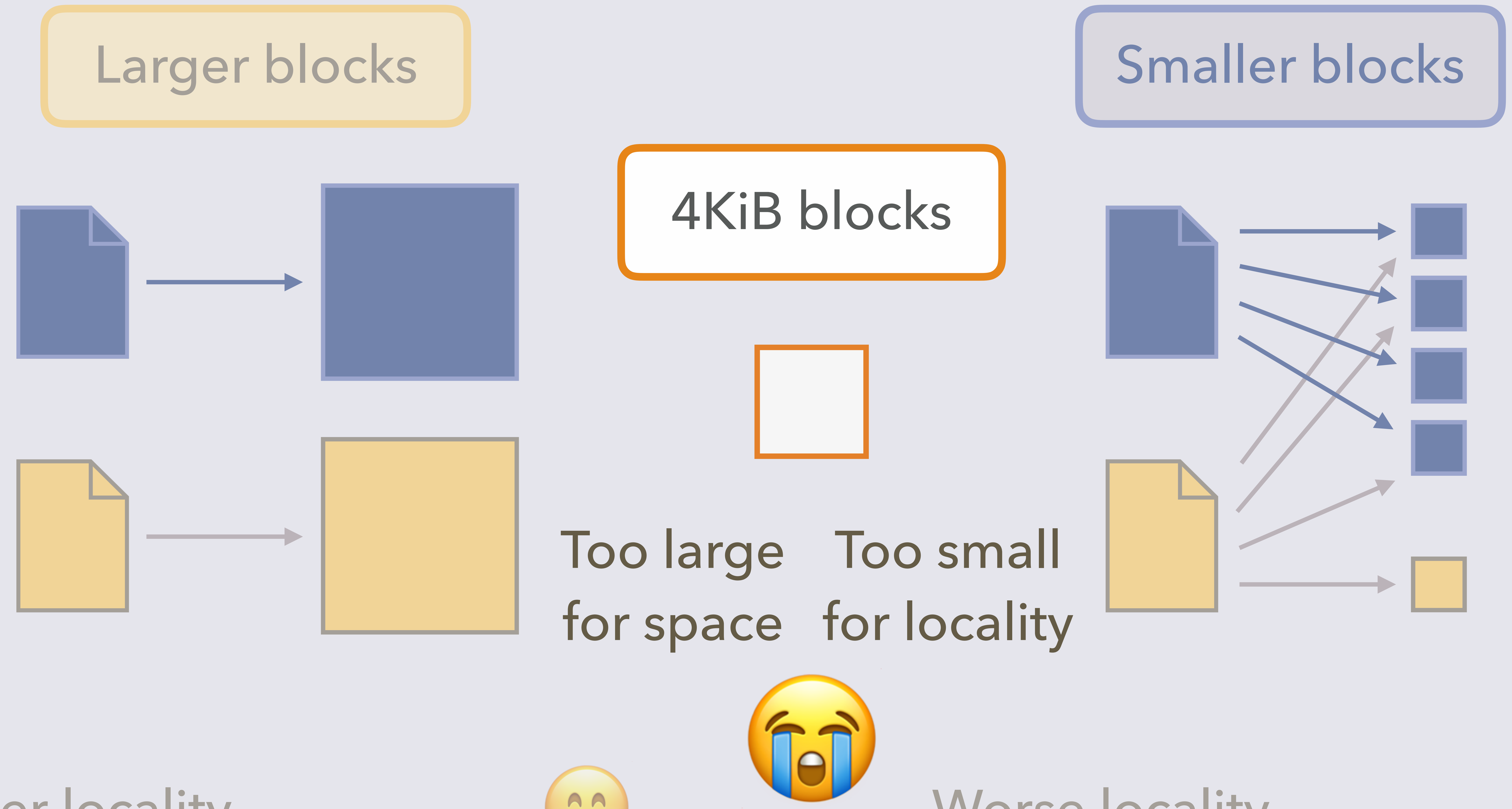

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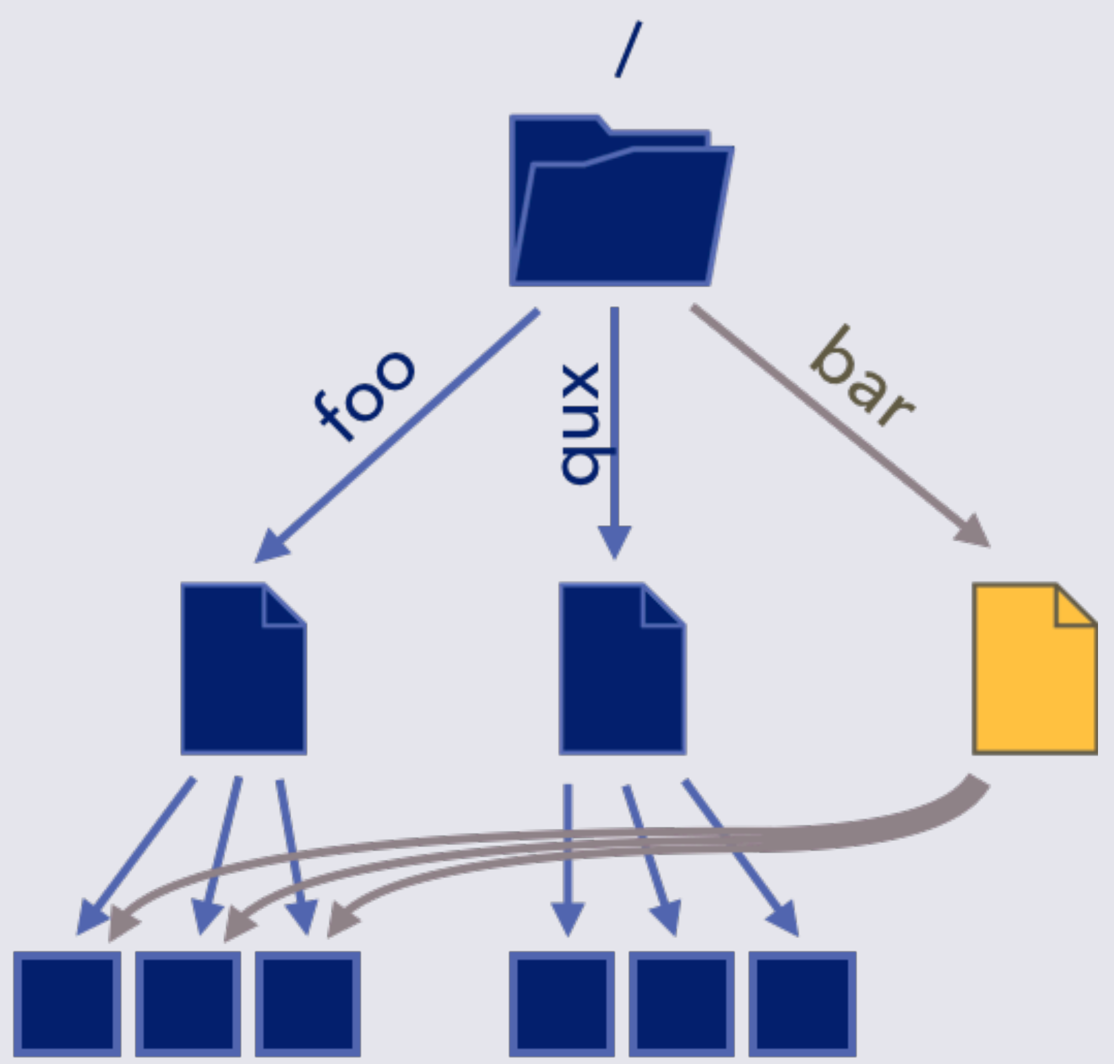
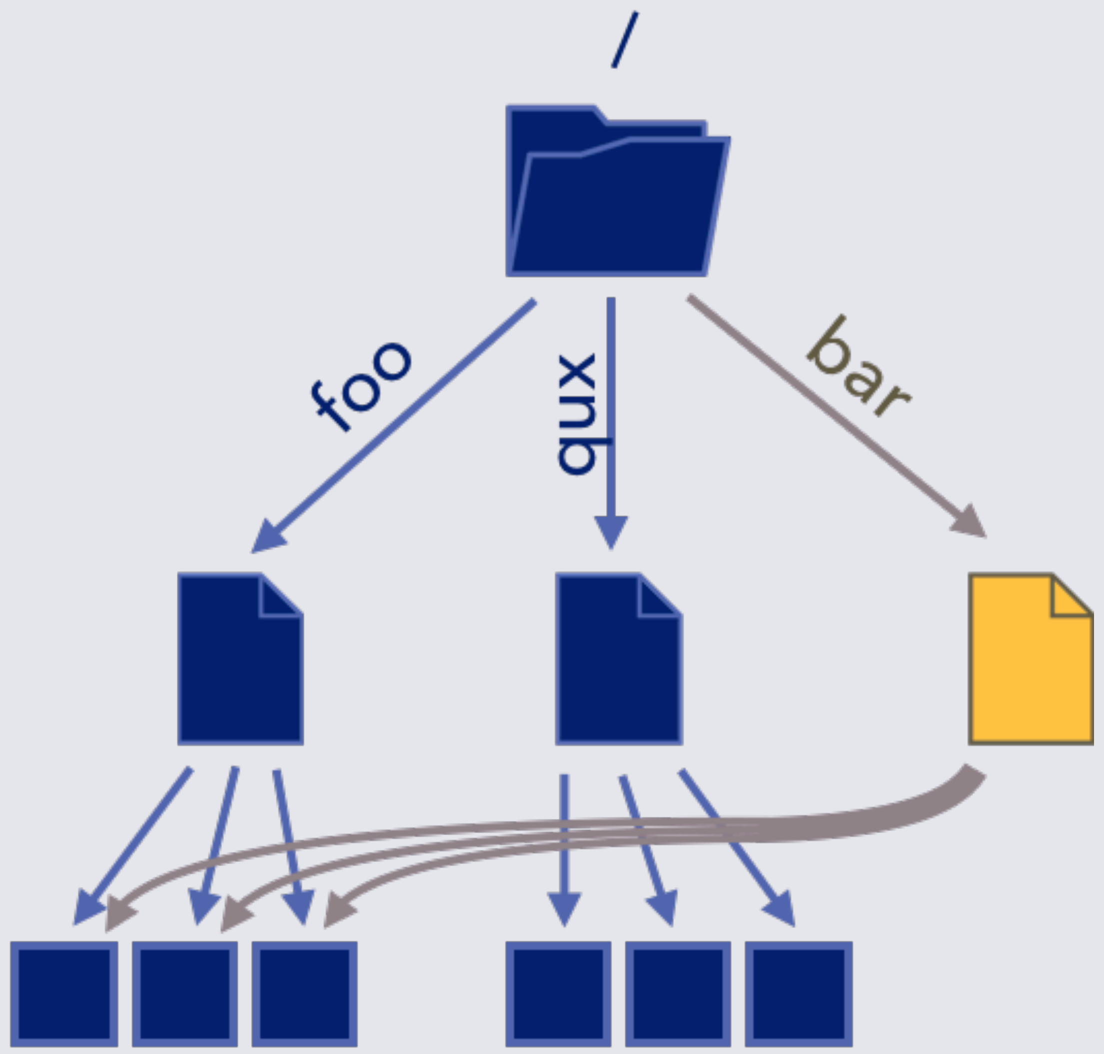
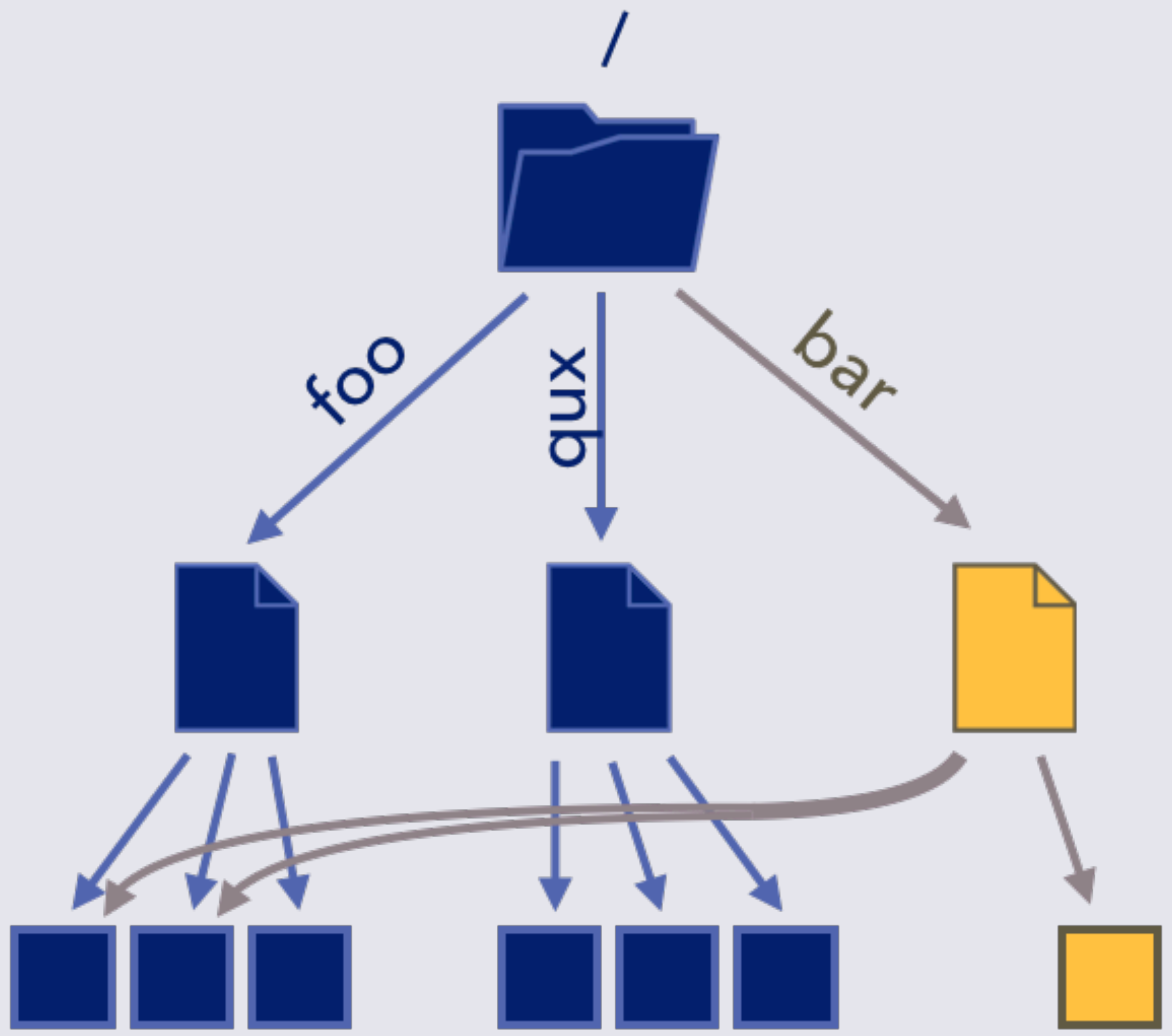
Inode Logical Copy Takeaway



Using a DAG to share data is great for latency

Inode Logical Copy Takeaway

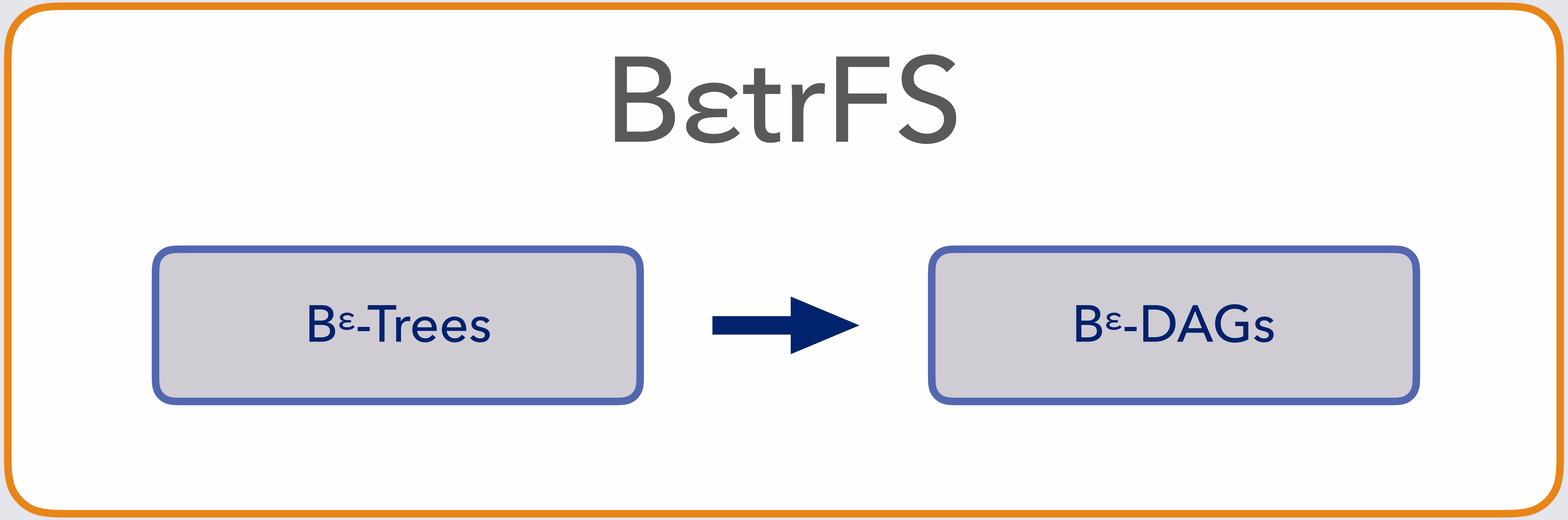




Using a DAG to share data is great for latency

Challenge:
Small writes break sharing

Our Solution: Bε-DAGs



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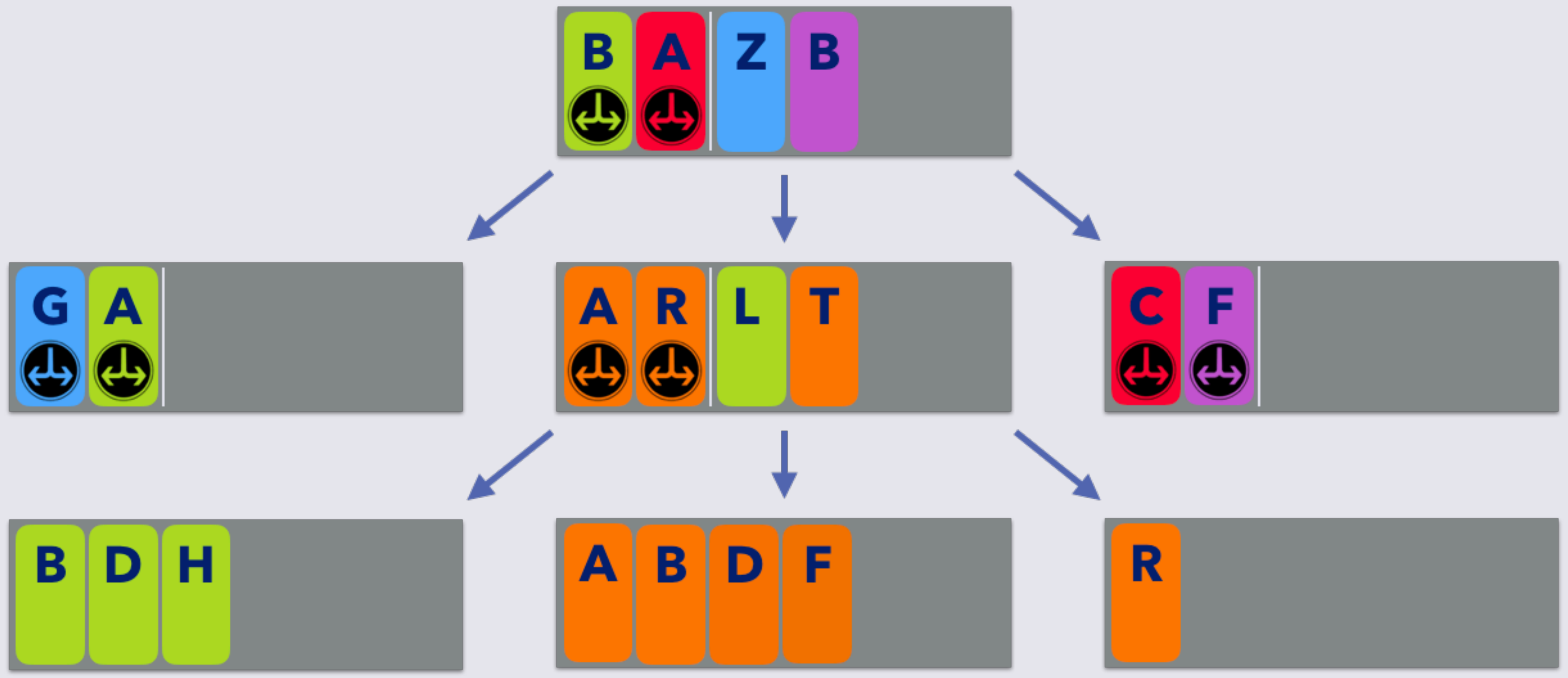

B$^\varepsilon$-trees have good locality and batch together small writes

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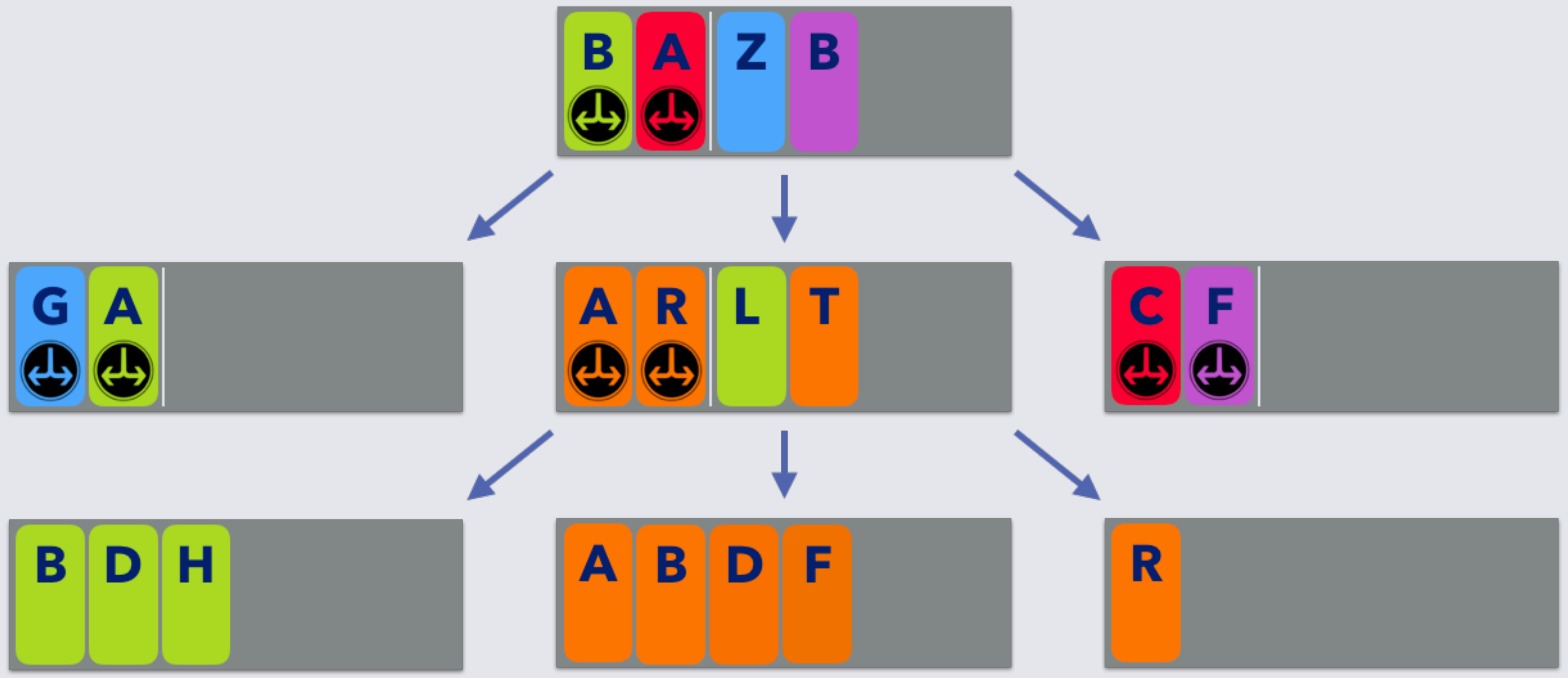
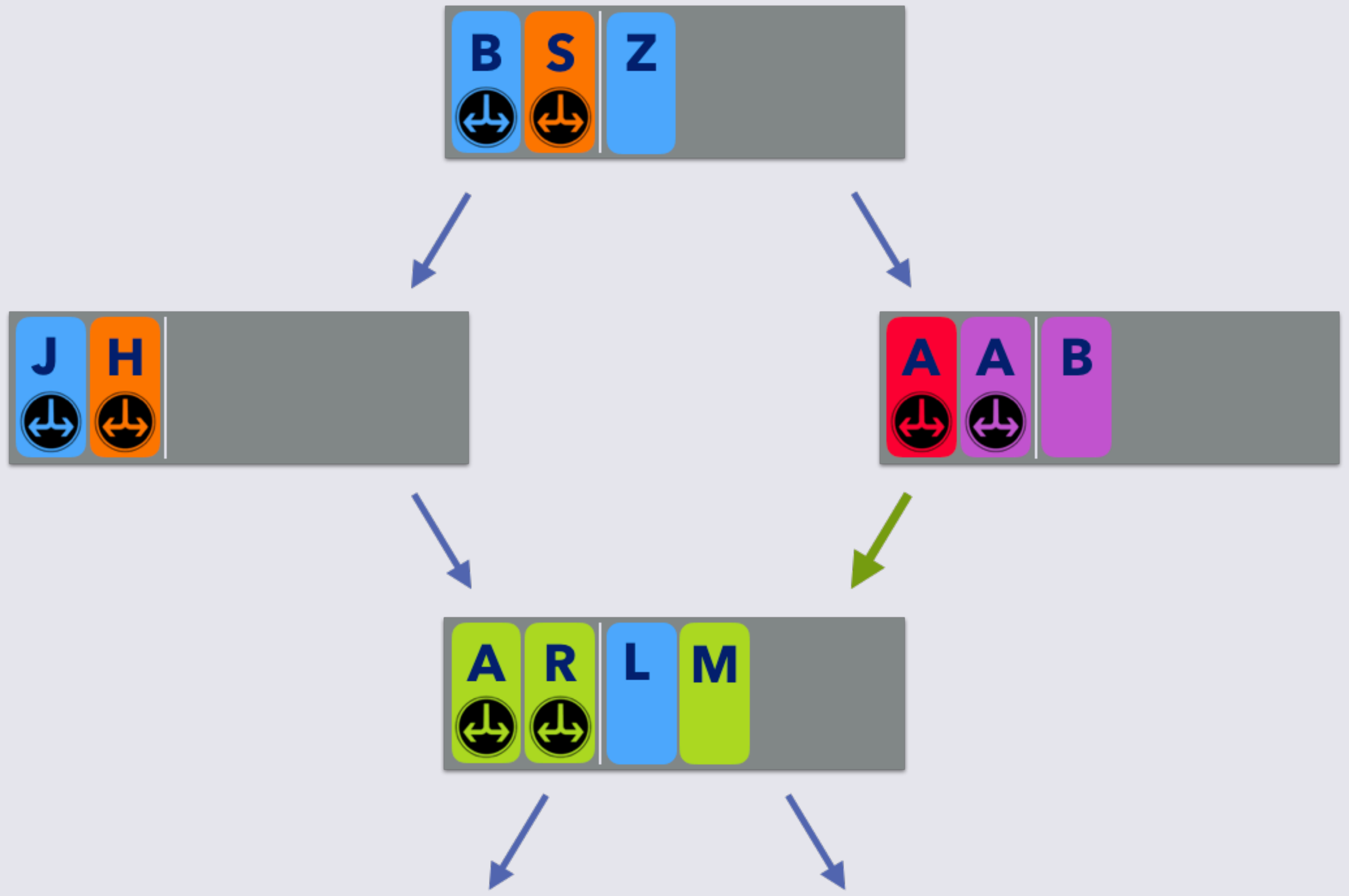




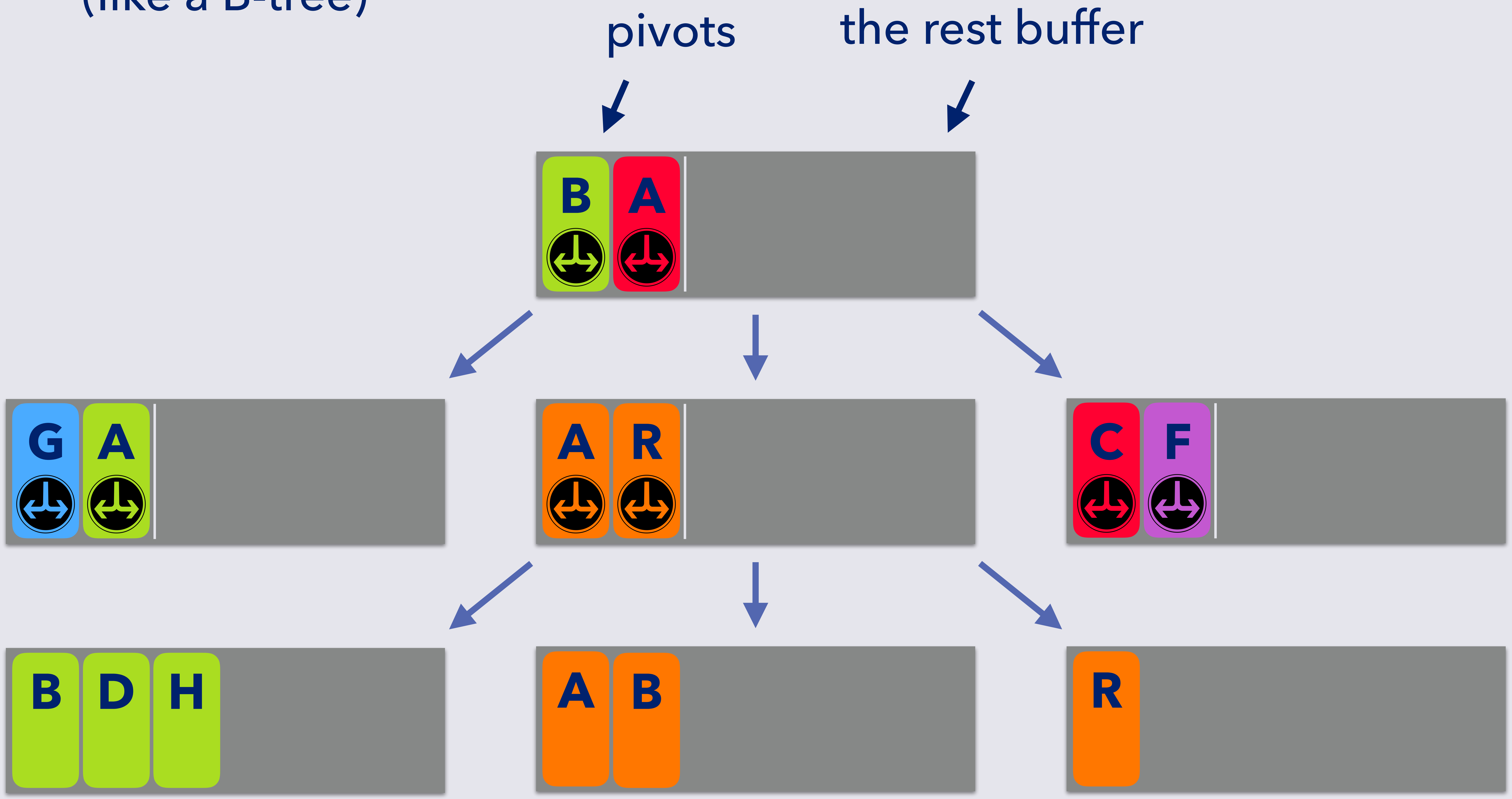
B$^\varepsilon$-trees have good locality and batch together small writes

In this paper, we turn B$^\varepsilon$-trees into B$^\varepsilon$-DAGs to share data between files

B^{ε}-Trees

B$^{\varepsilon}$-Trees

A B$^{\varepsilon}$-tree is a search tree
(like a B-tree)



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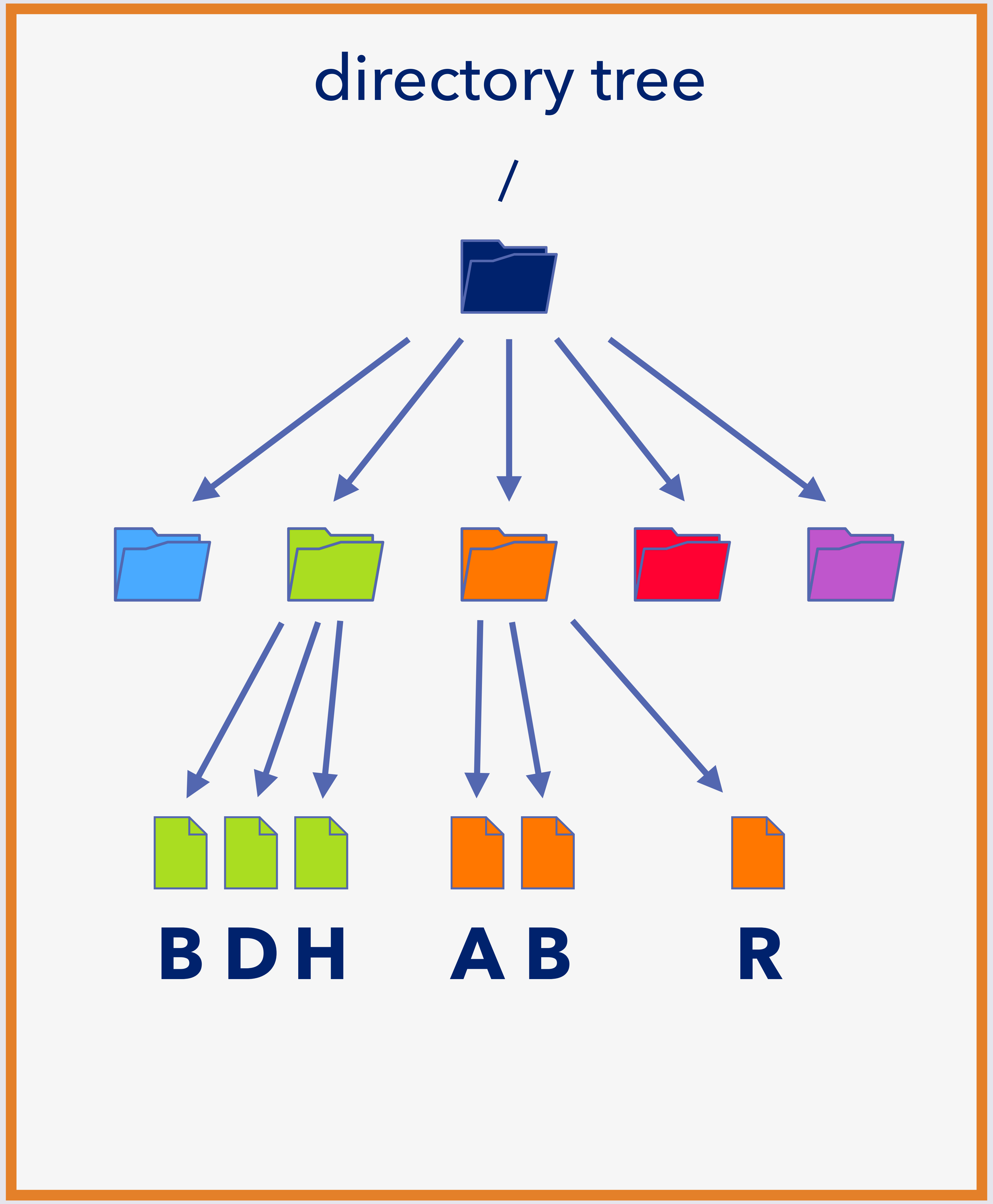

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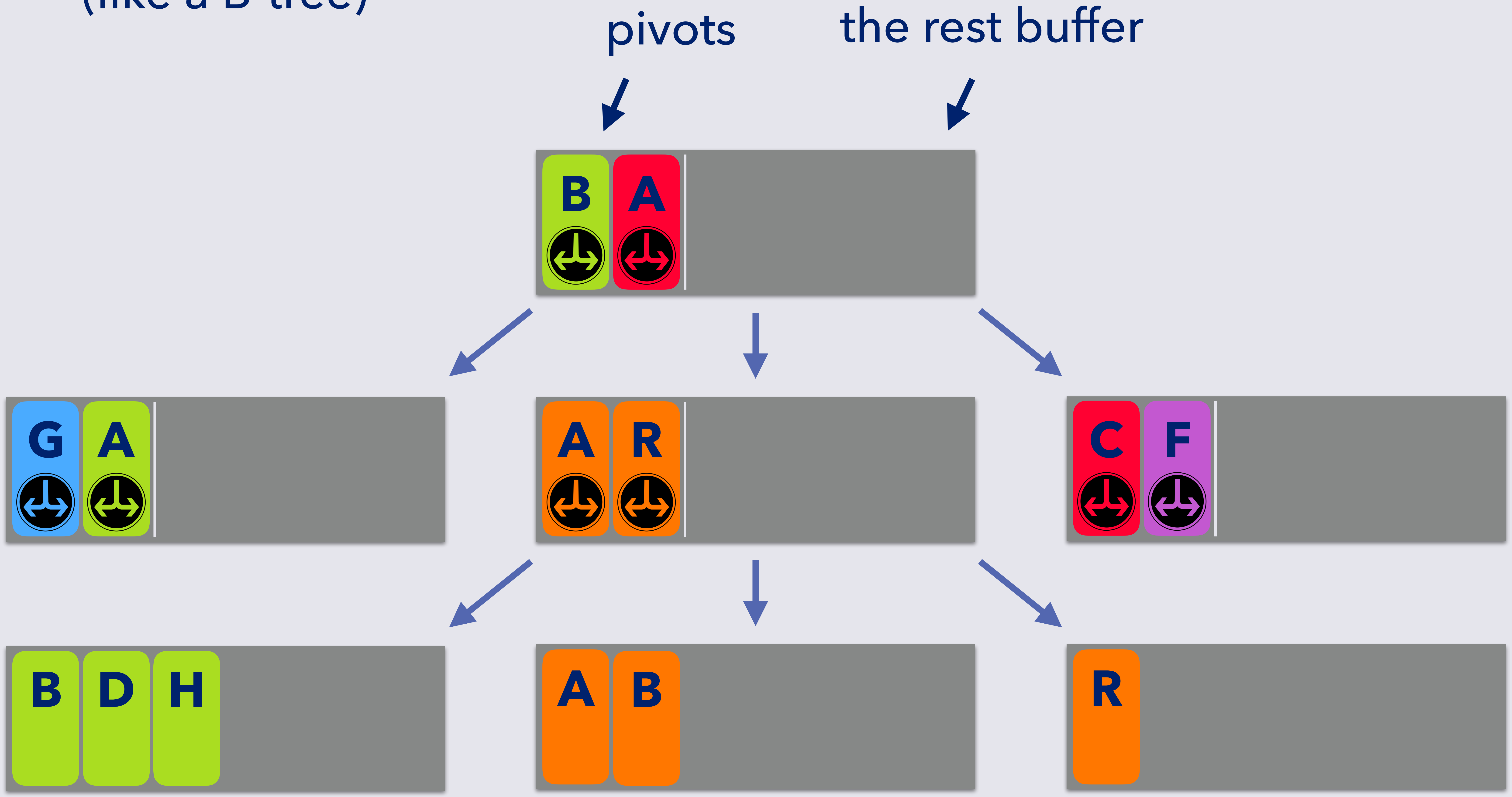

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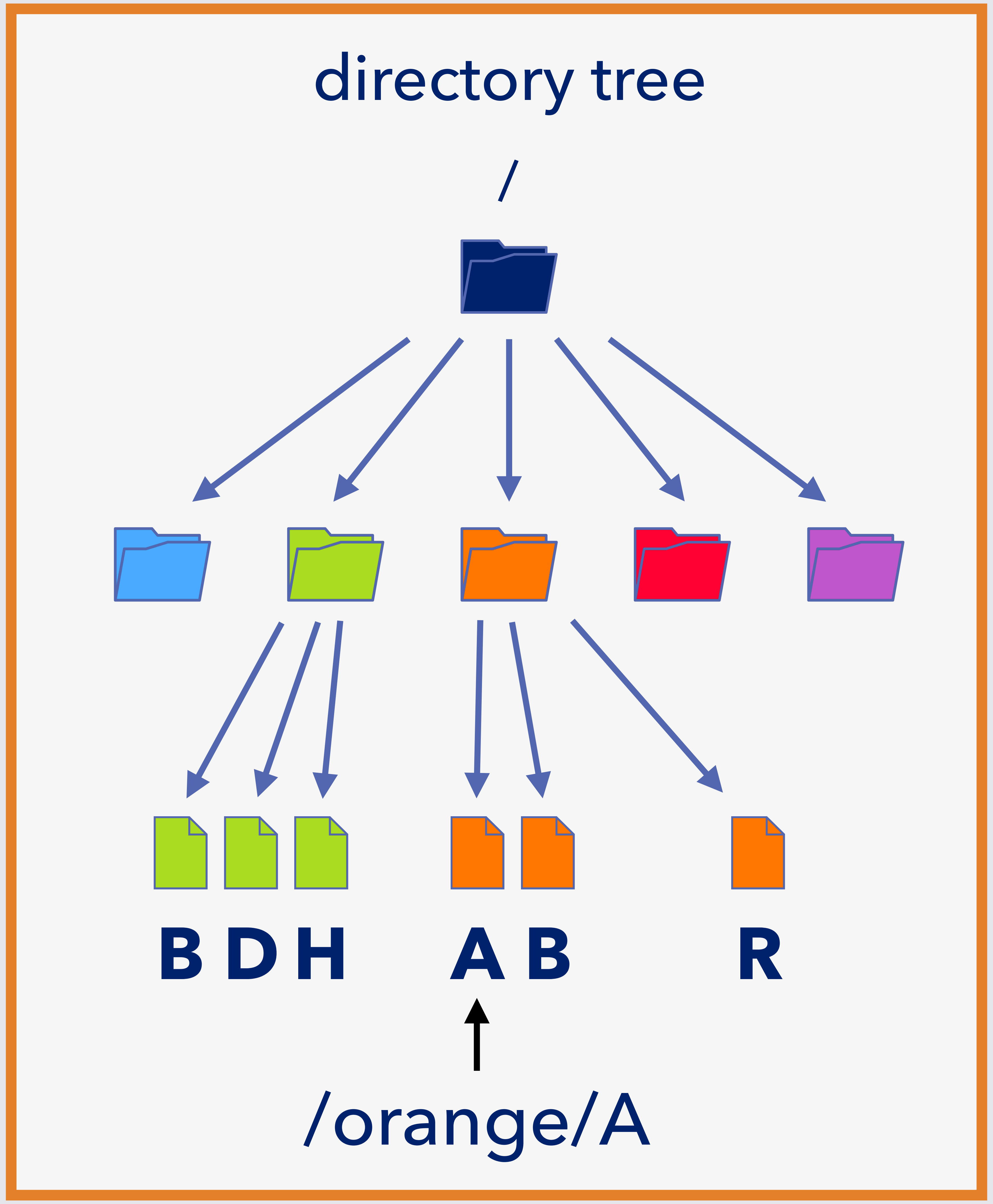

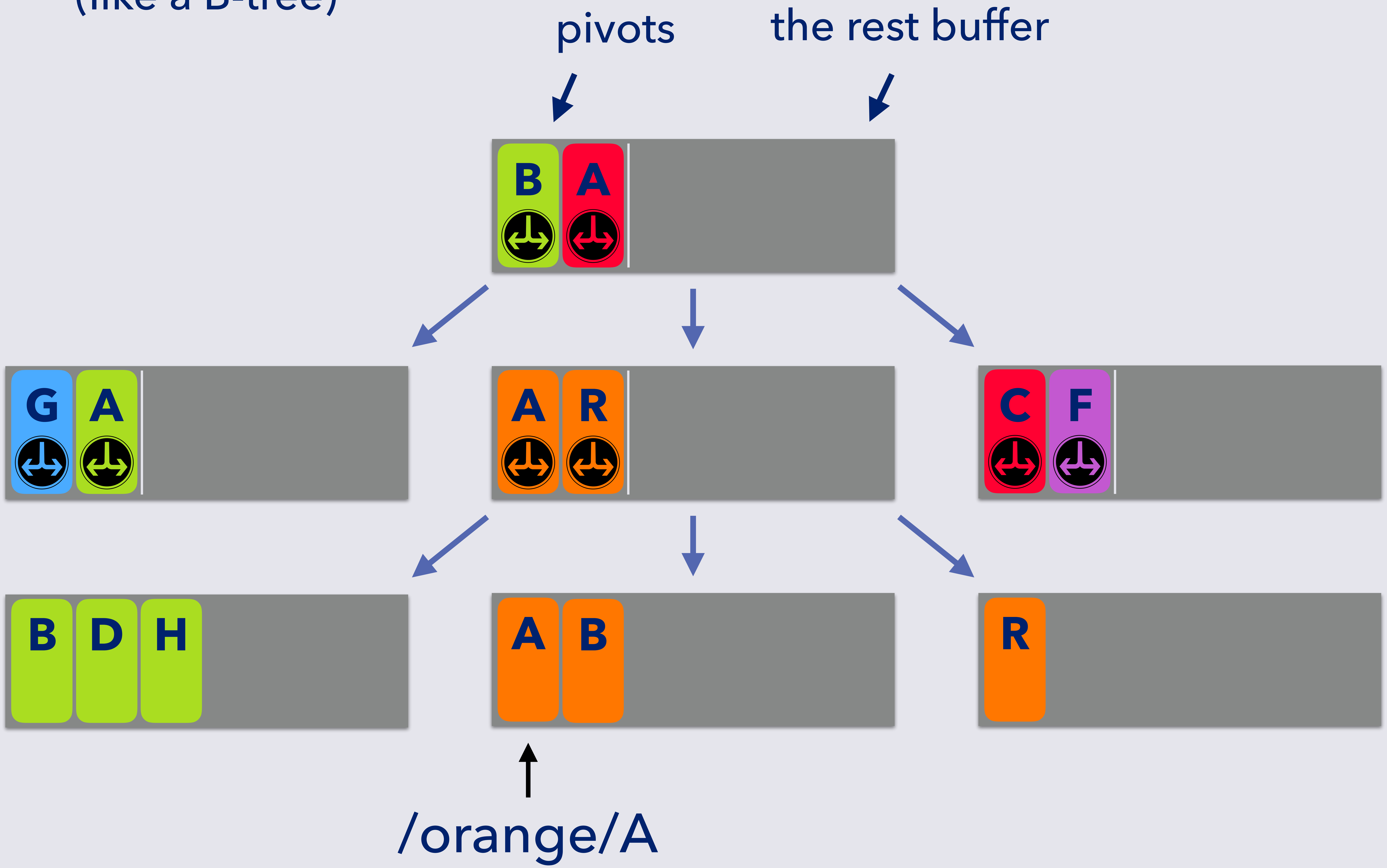

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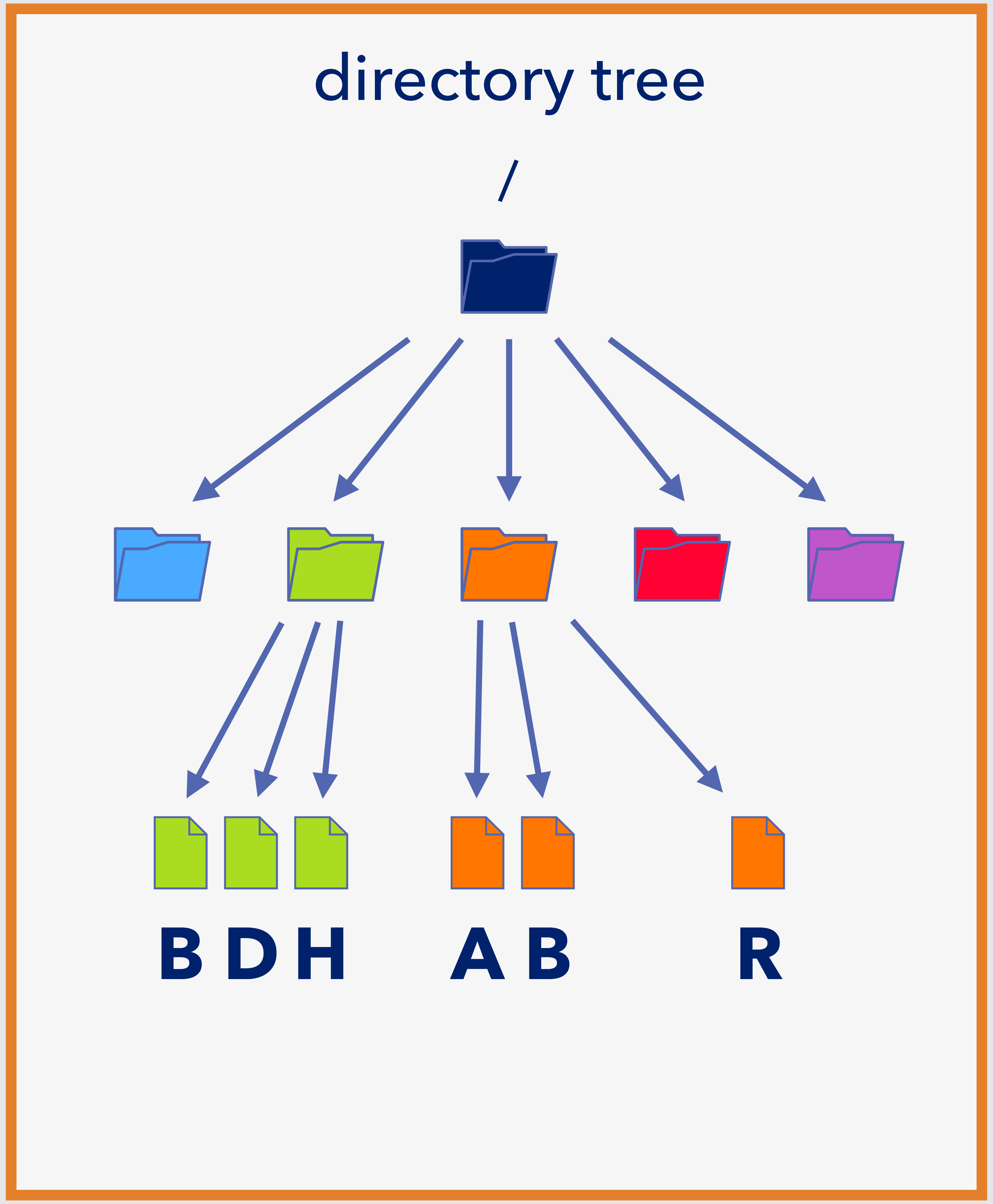
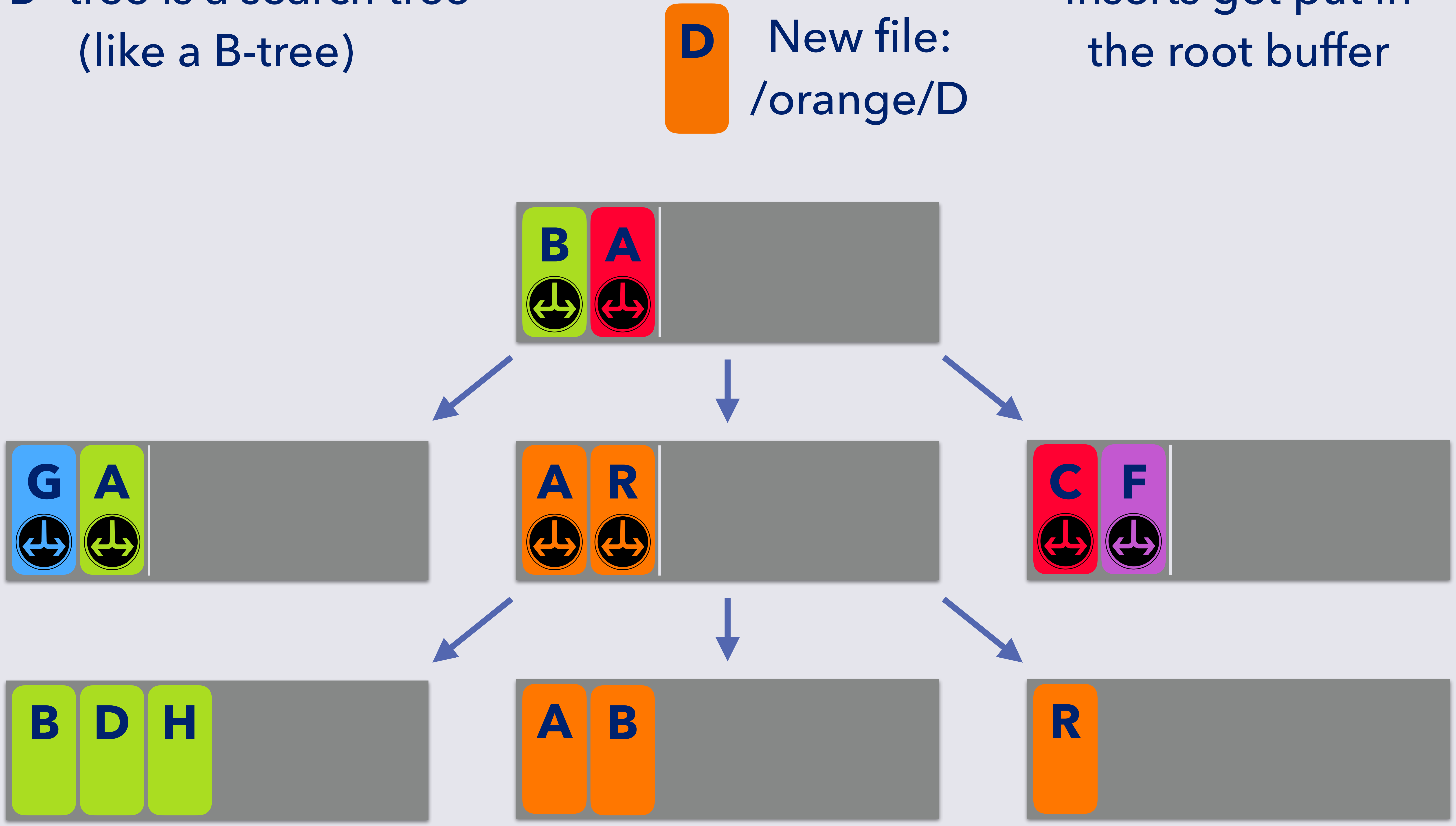


A B$^\varepsilon$-tree is a search tree (like a B-tree)

New file: /orange/D

Inserts get put in the root buffer



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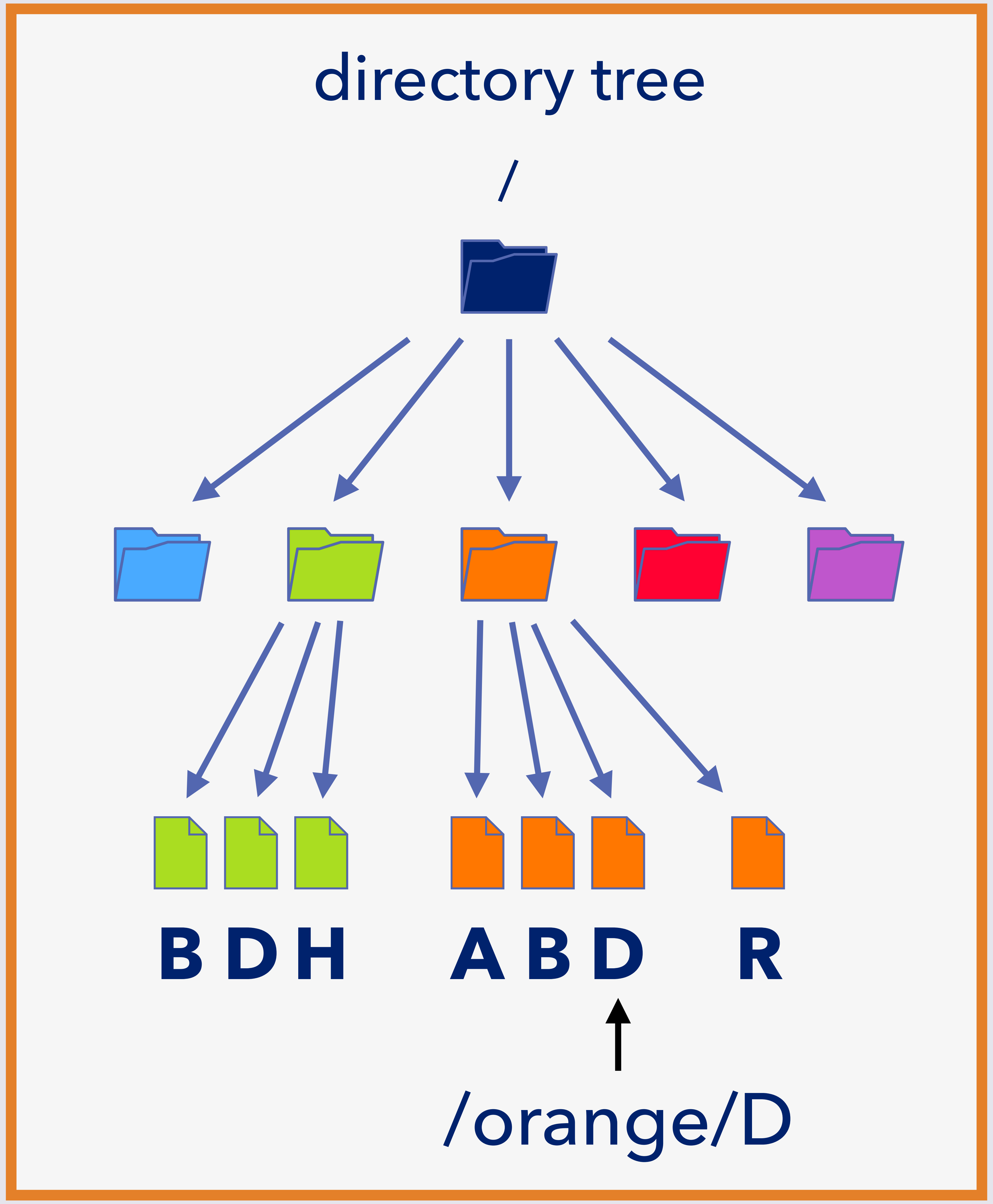

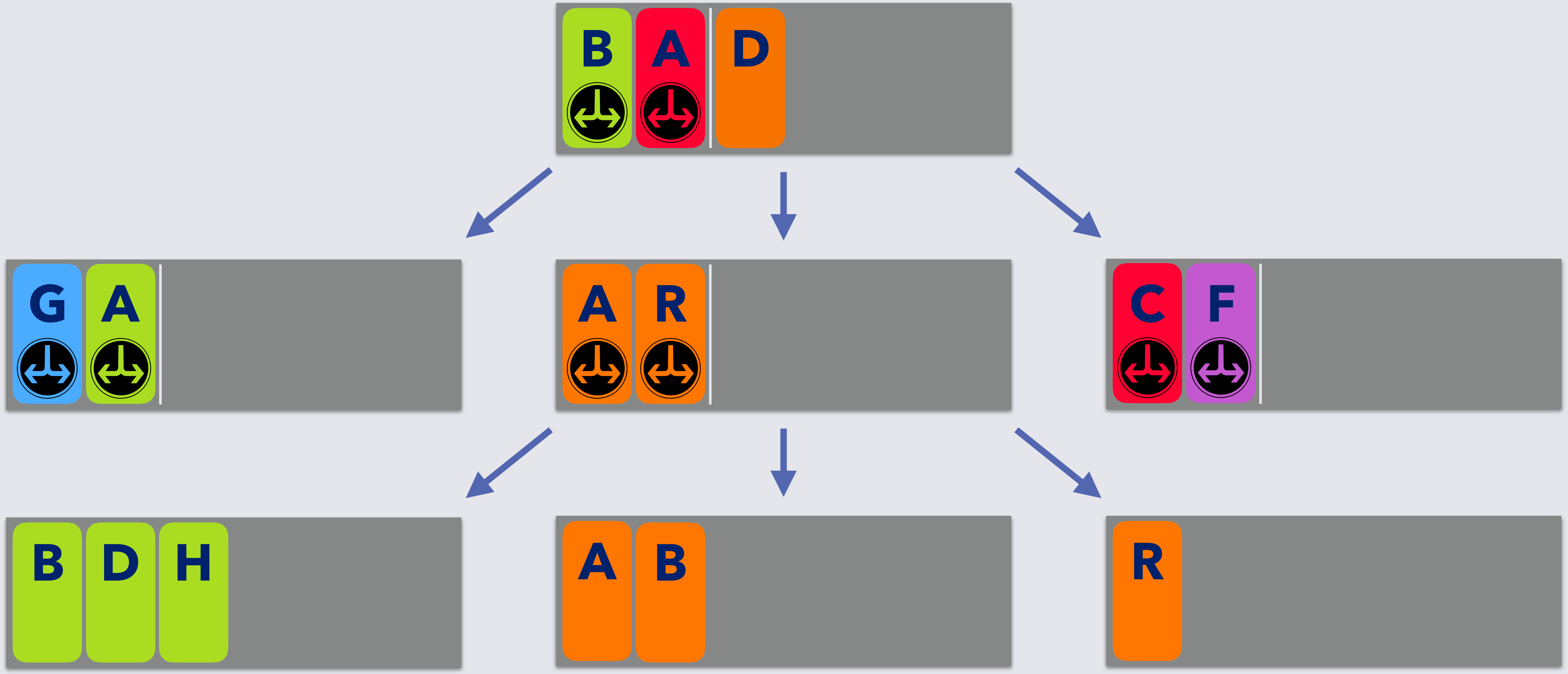

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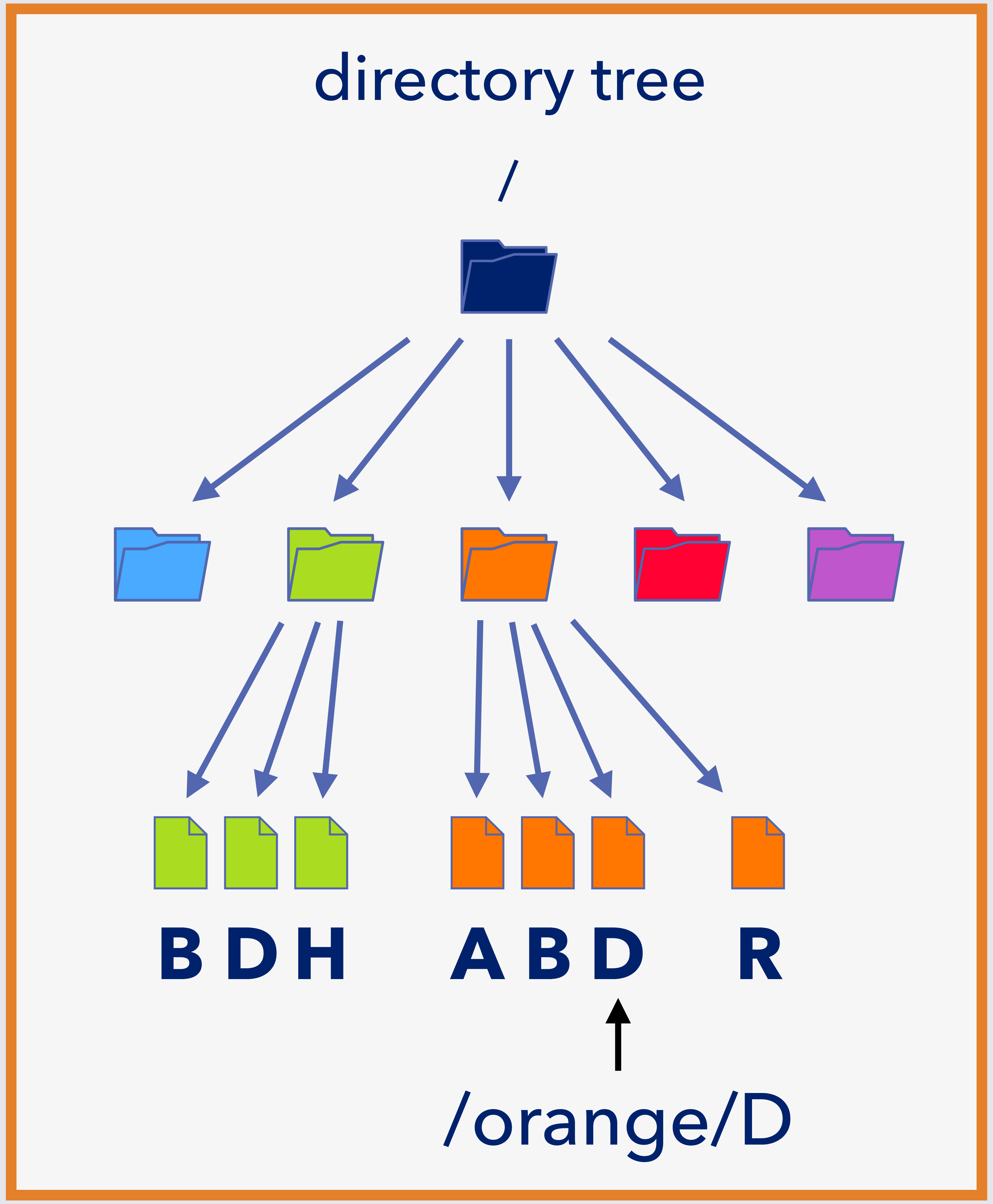

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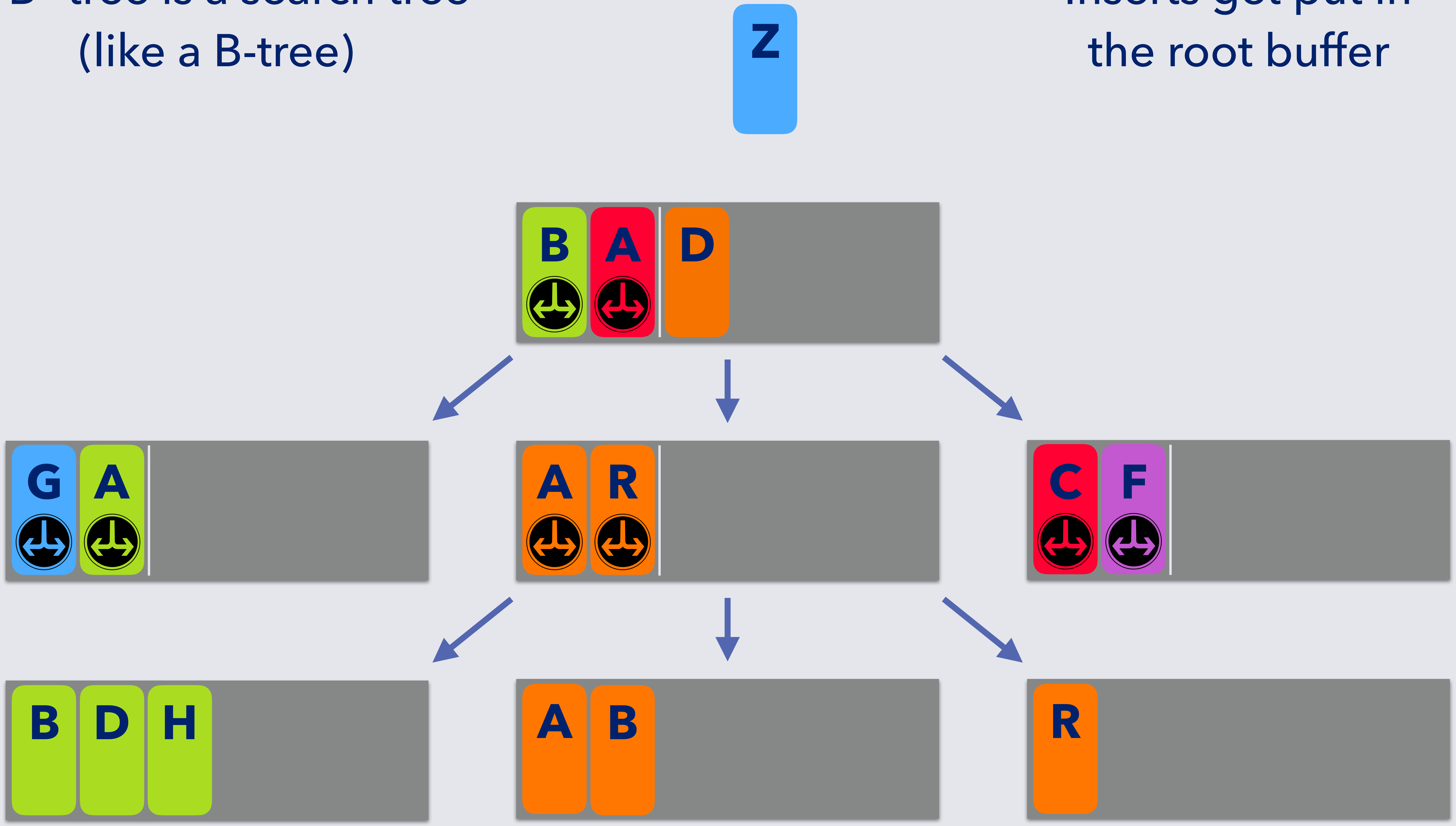

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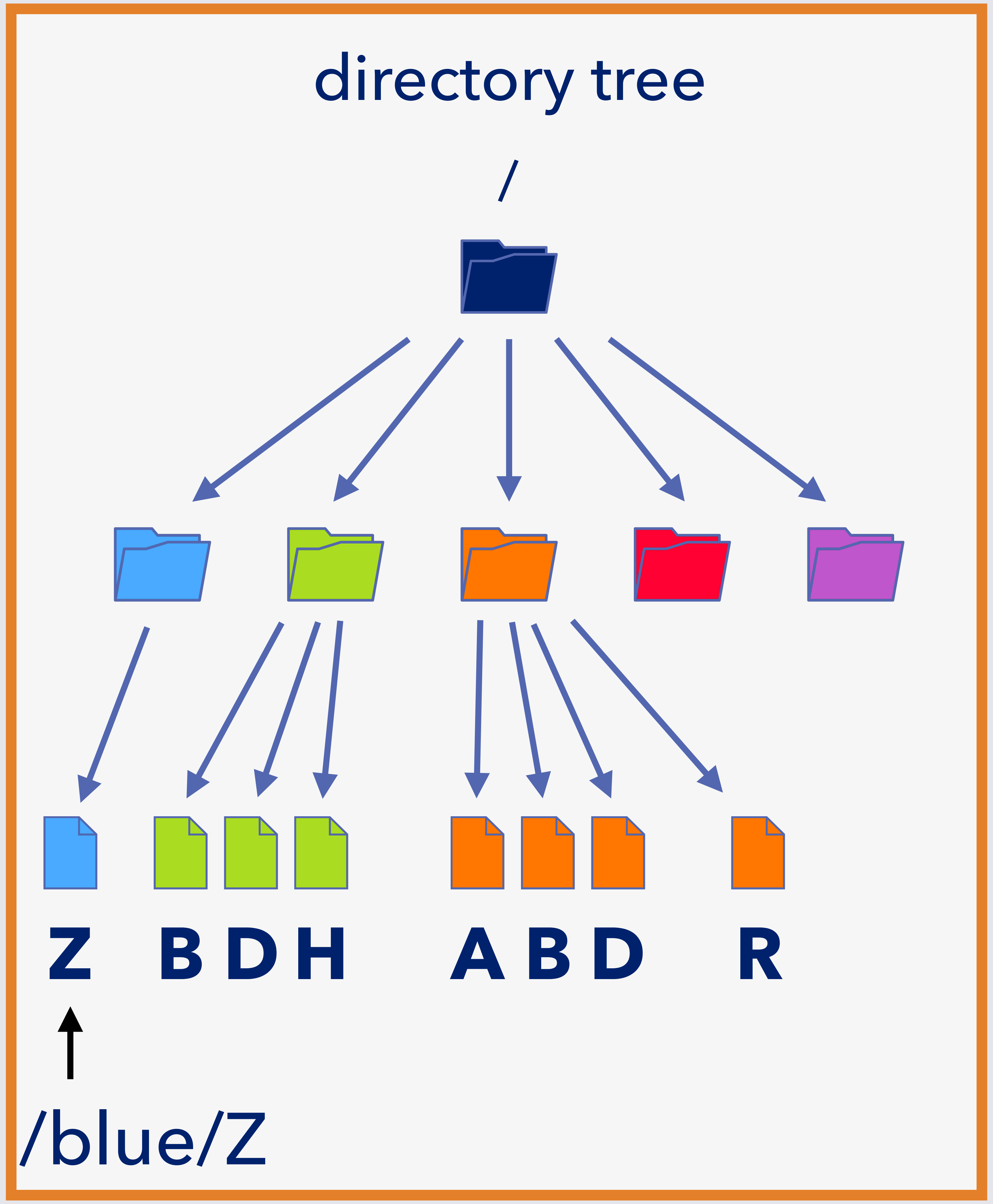

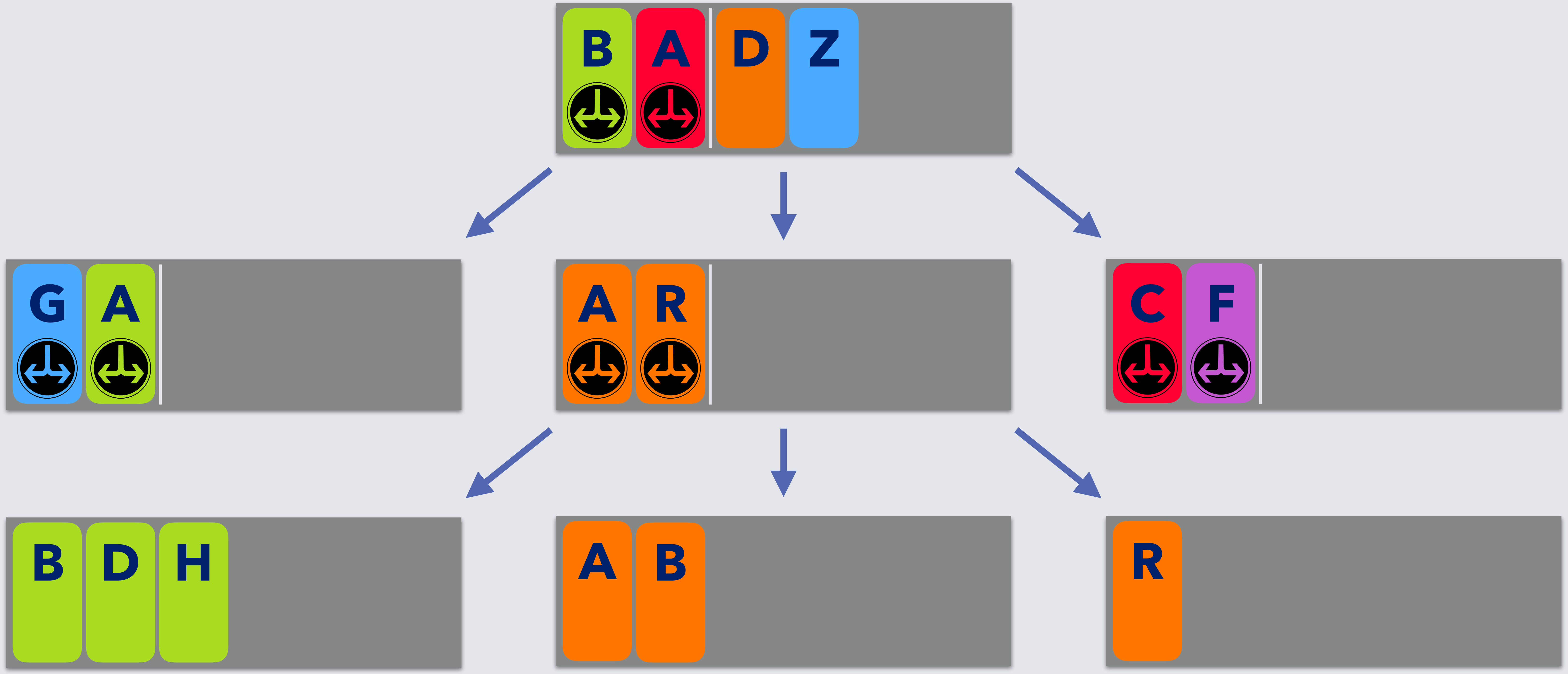

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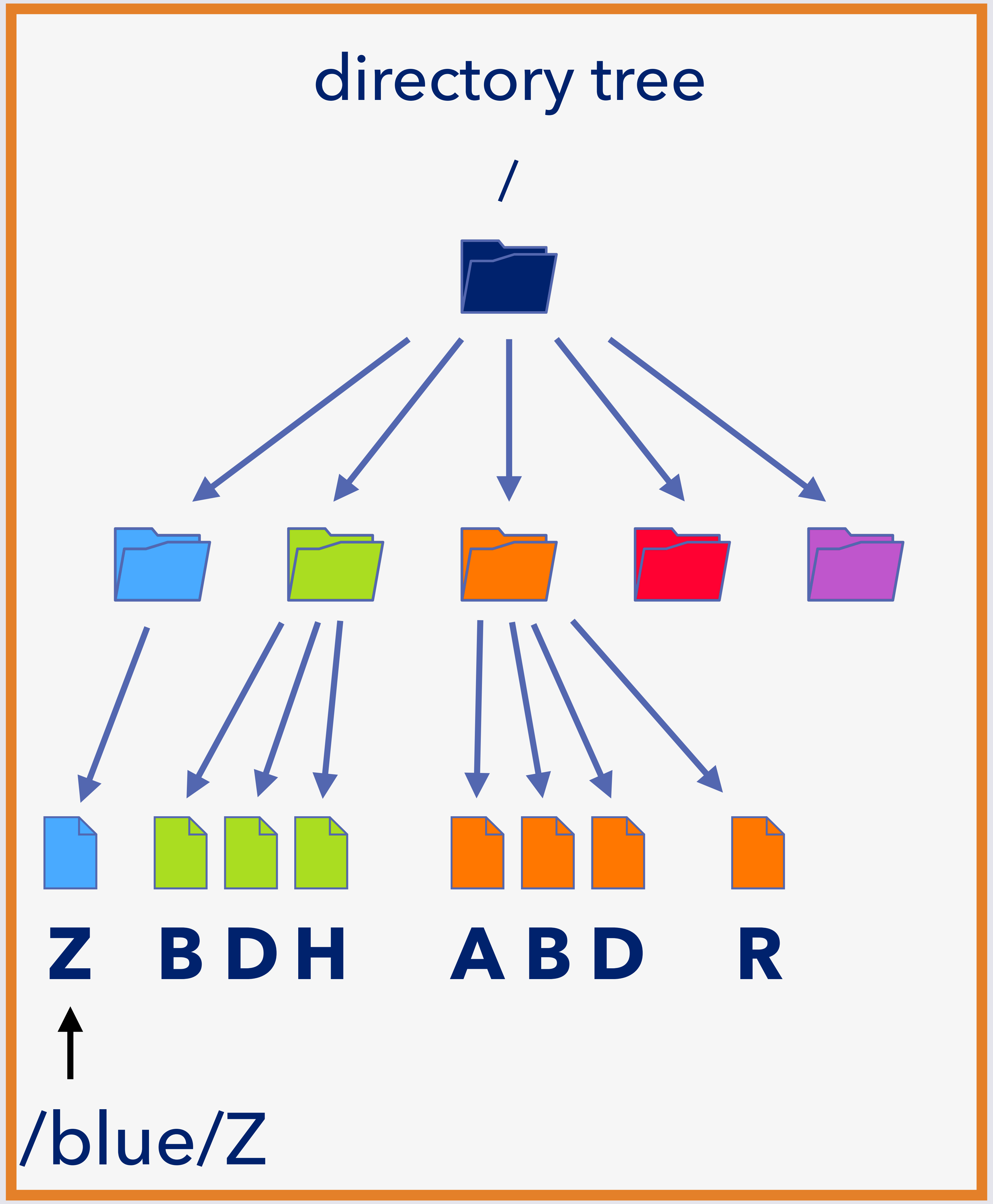

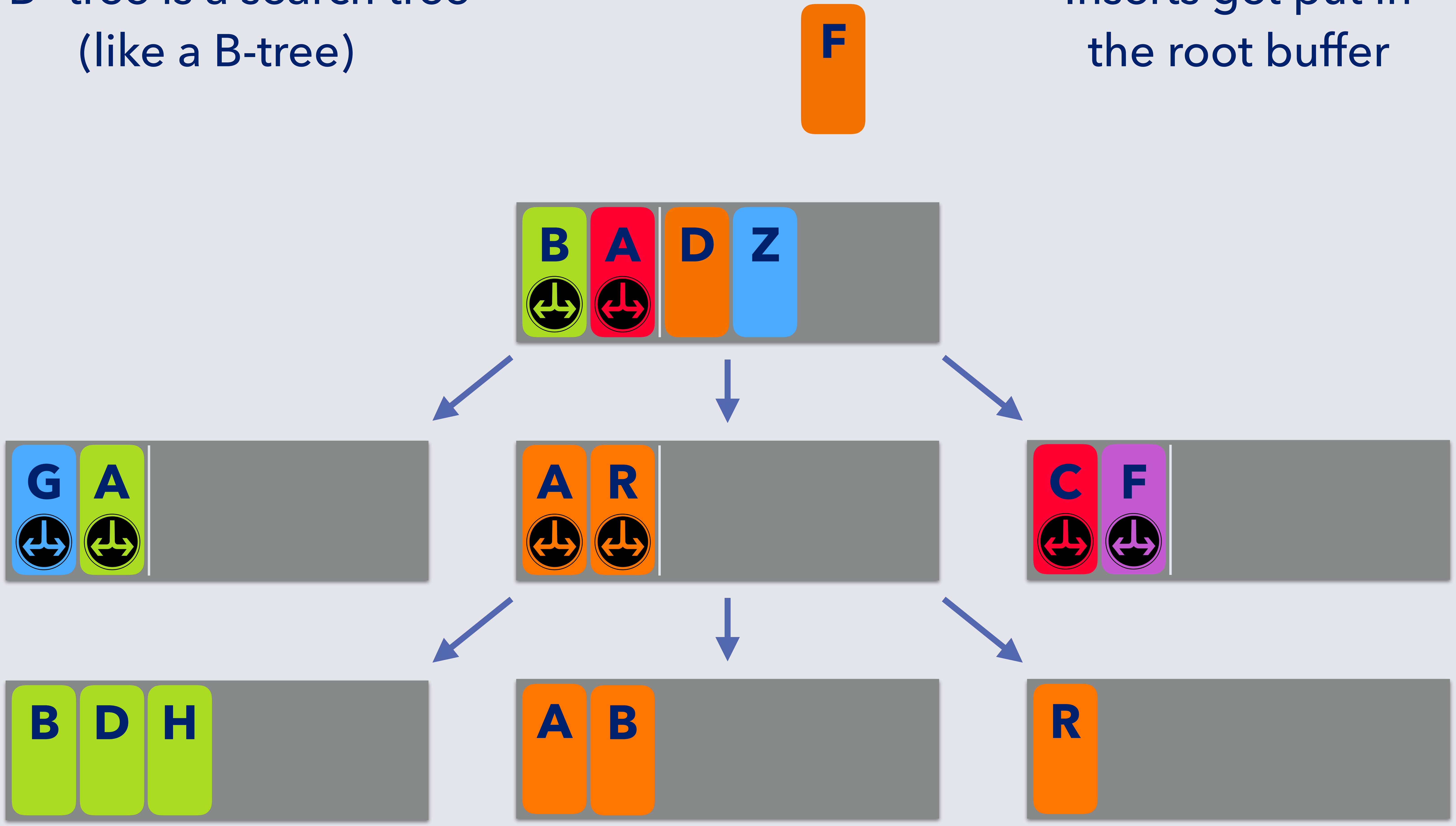

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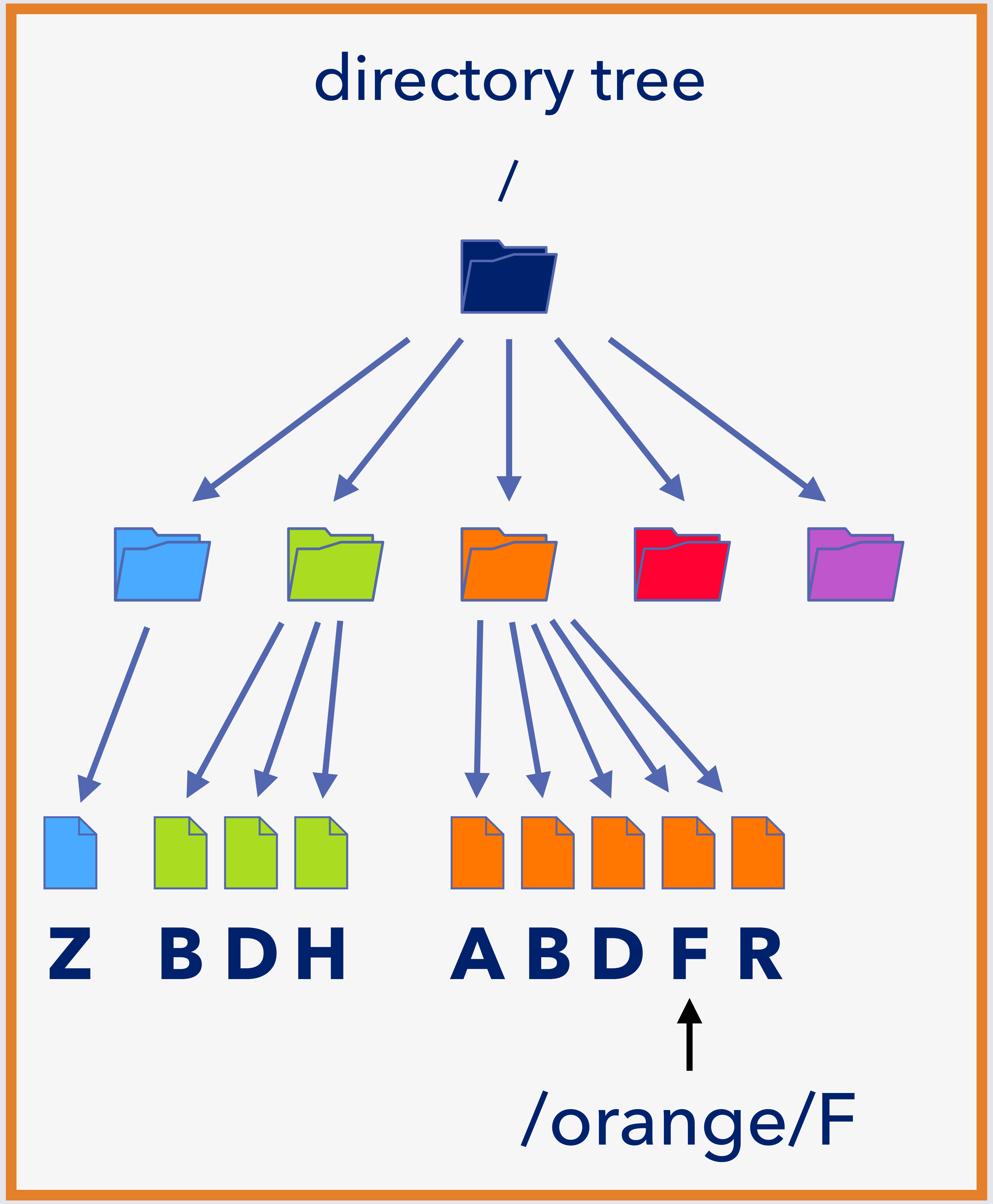

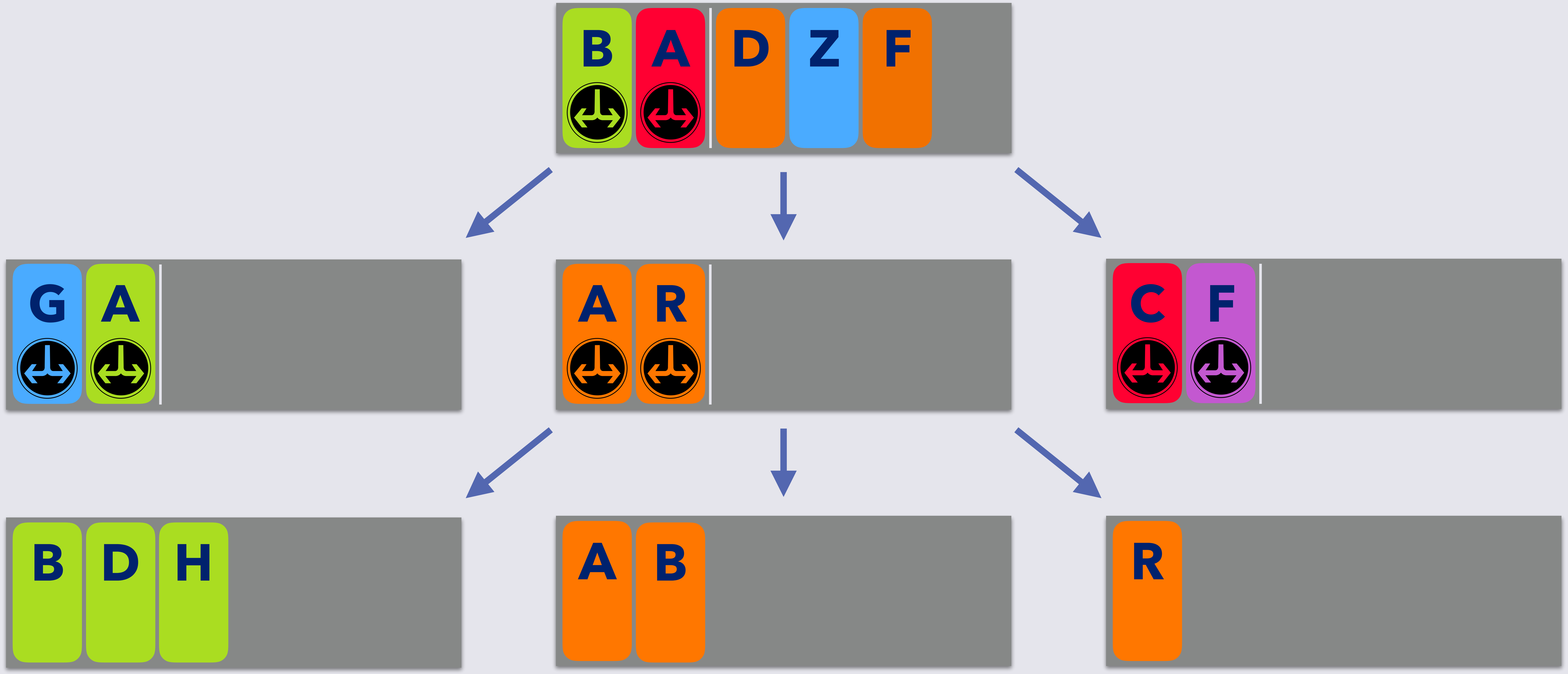

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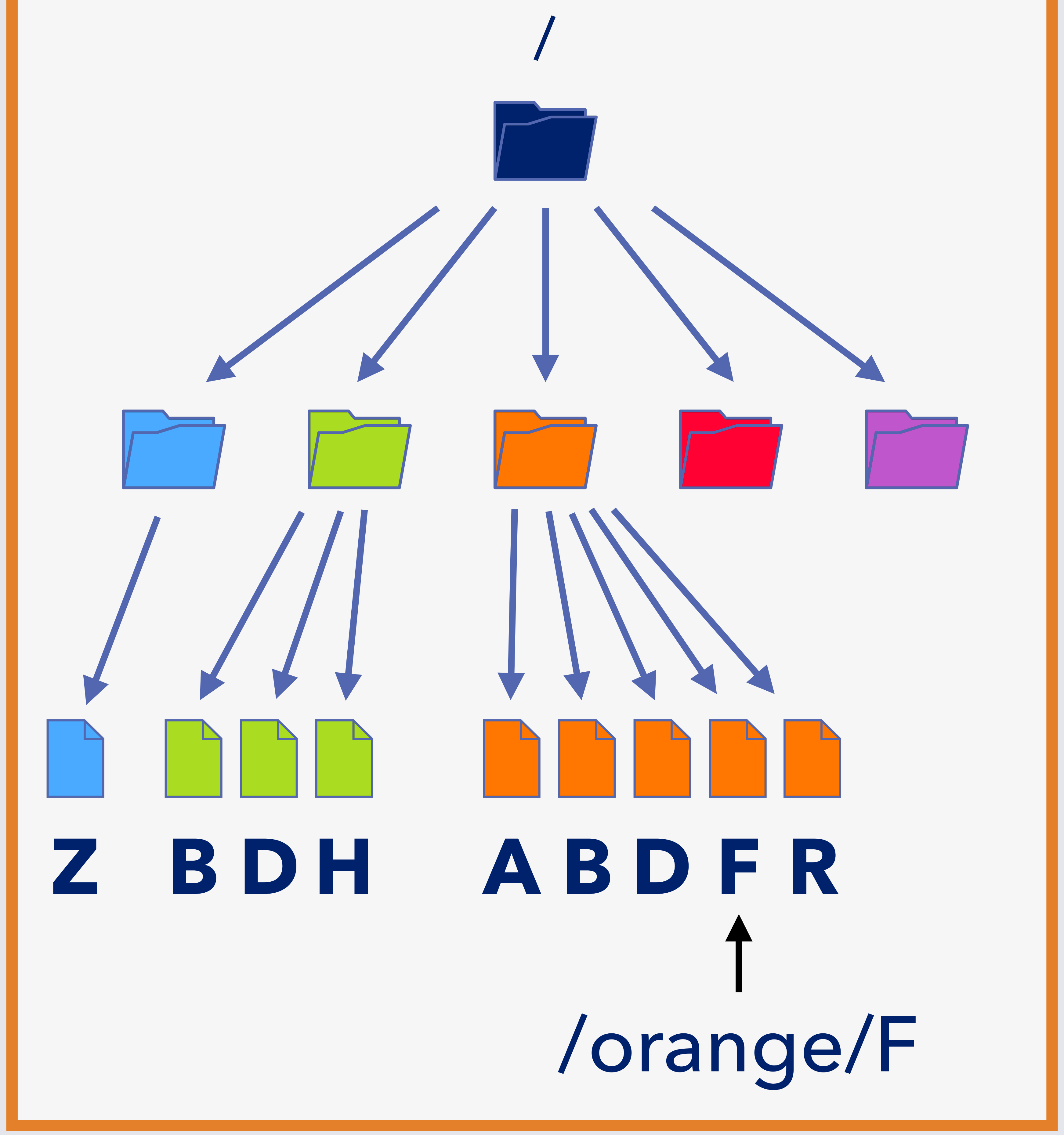
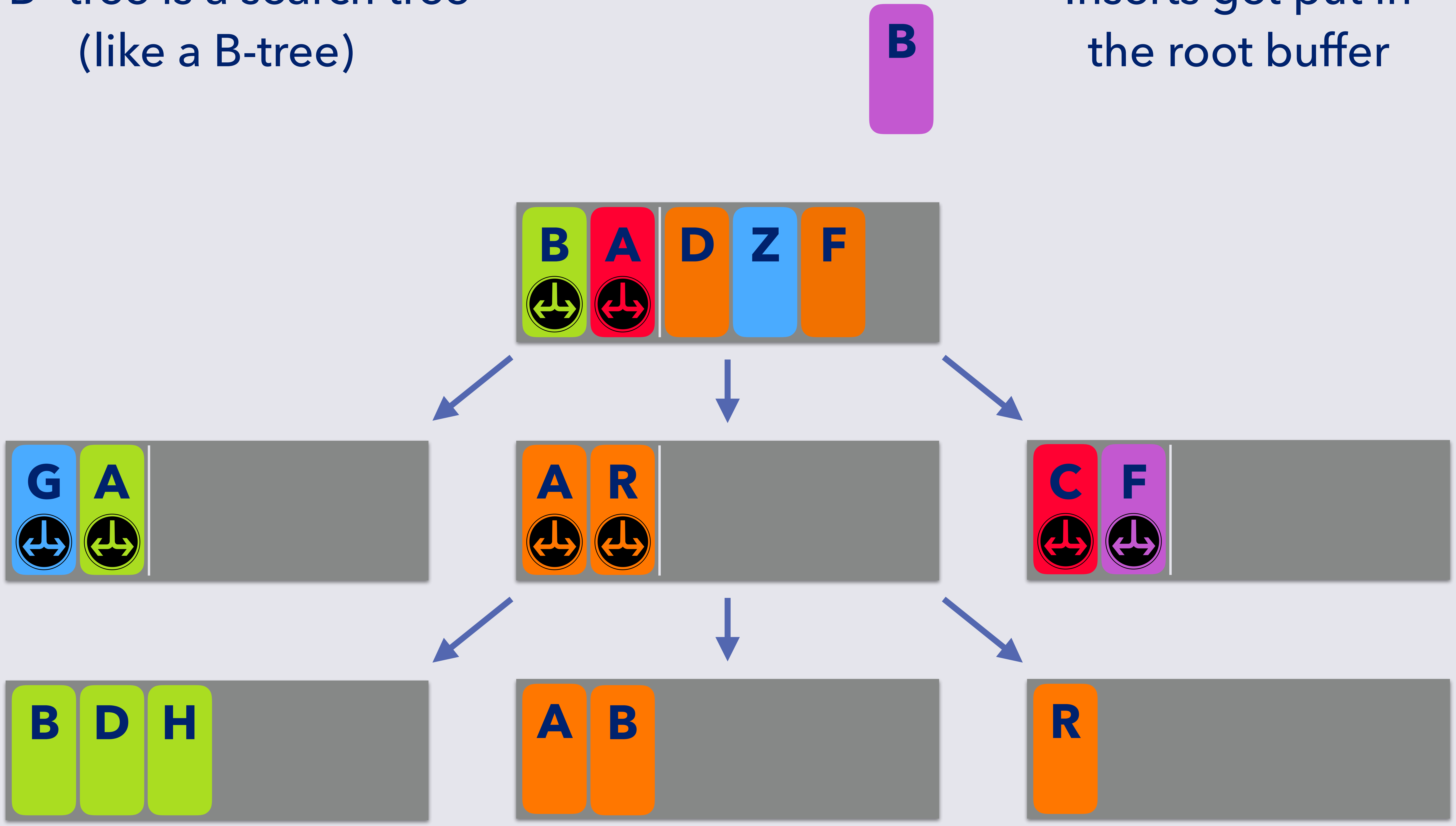
directory tree





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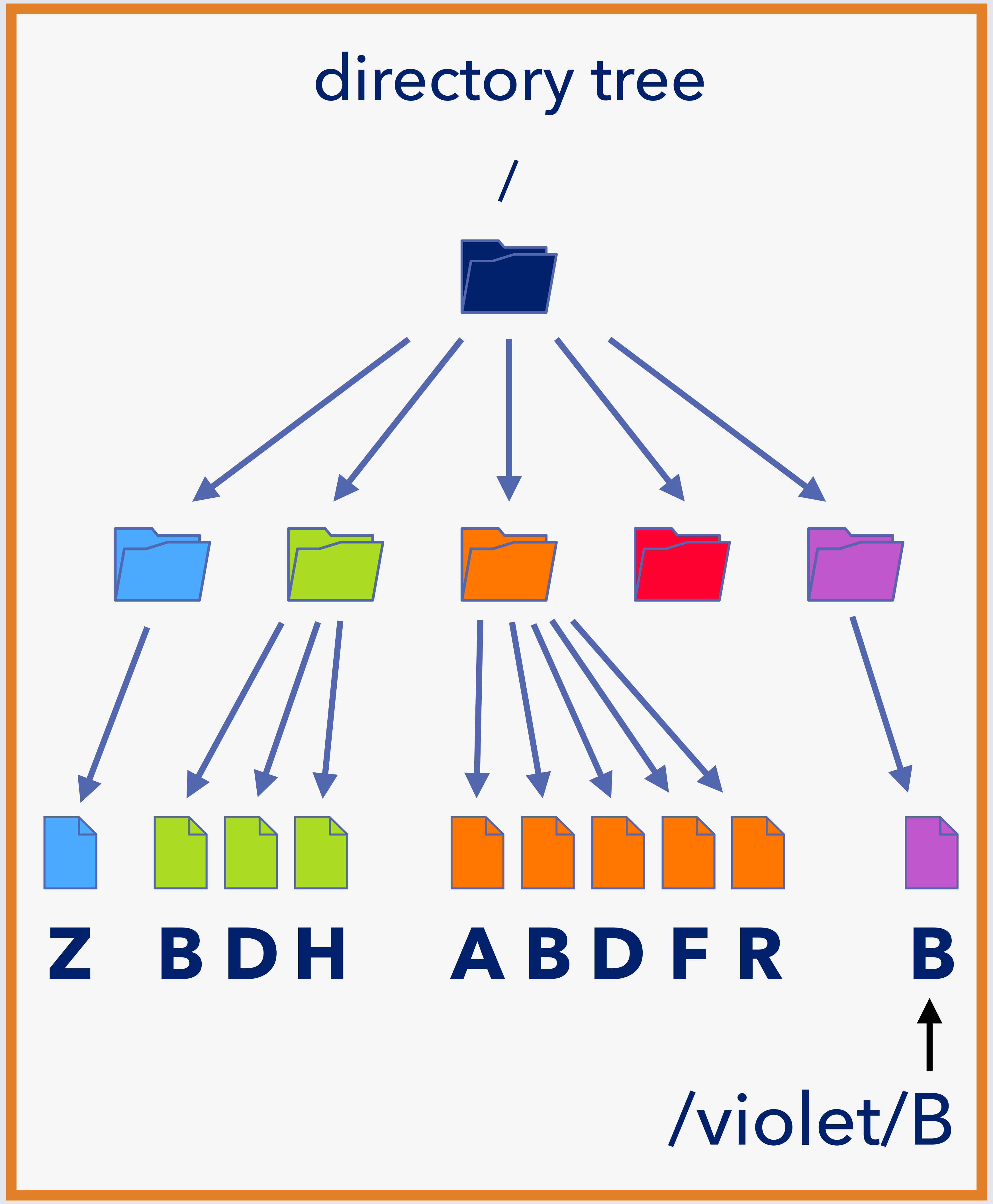
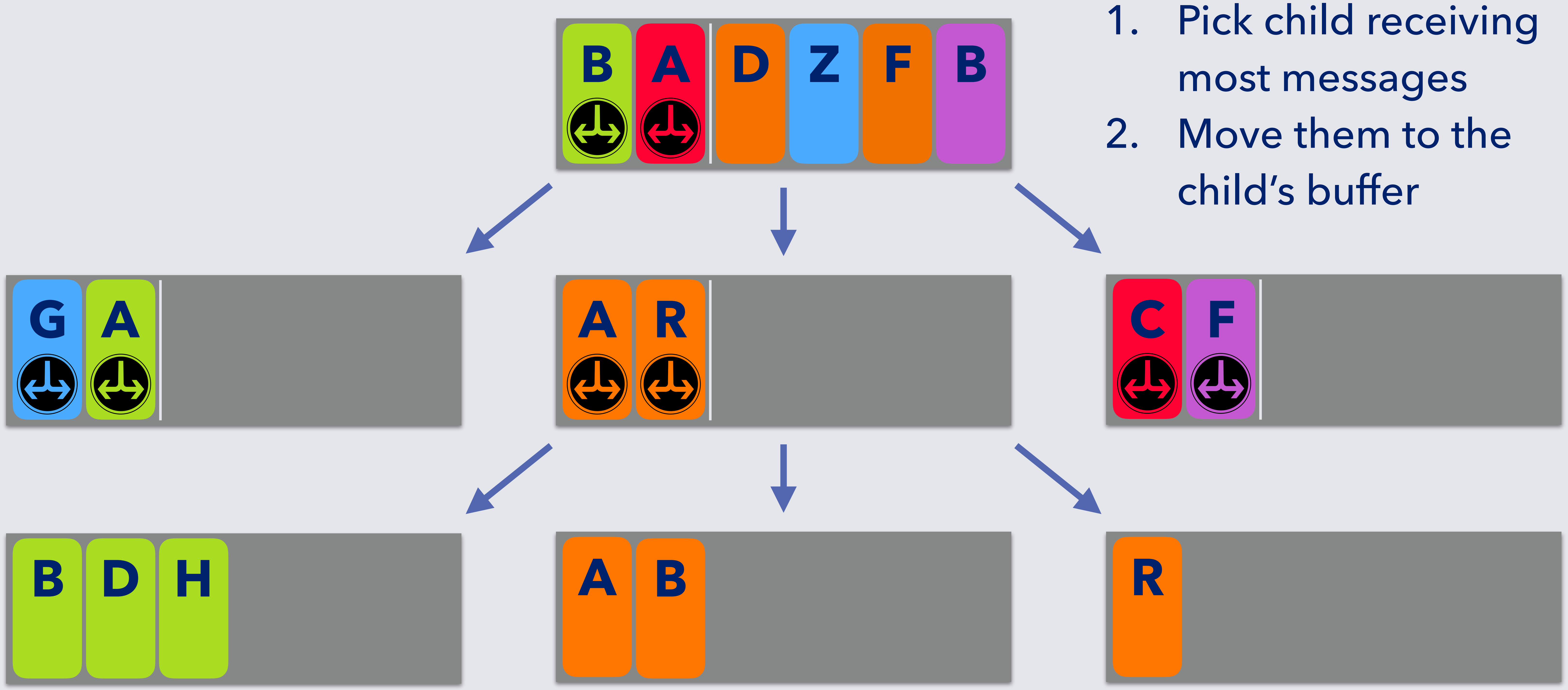
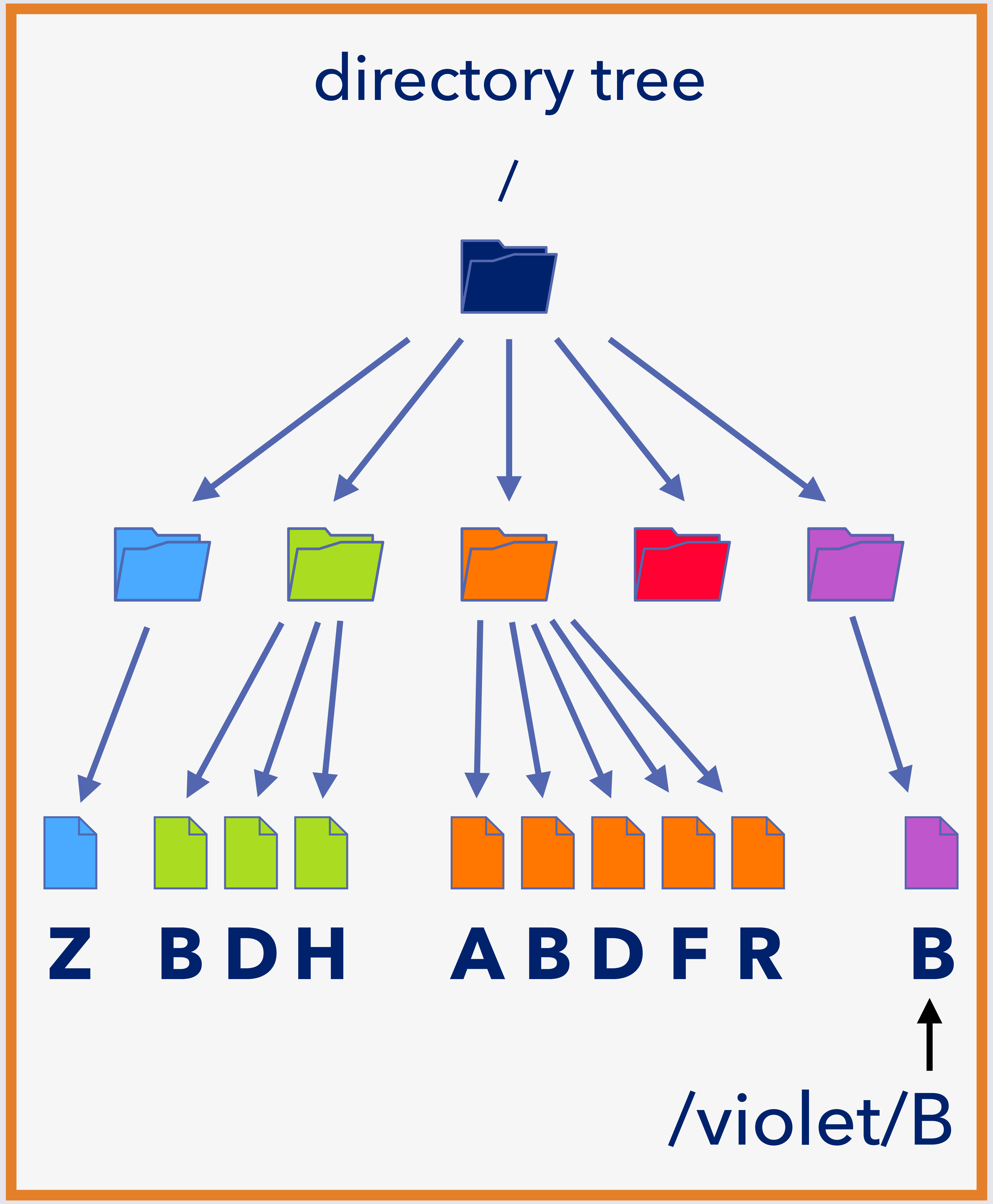
When a buffer is full:

1. Pick child receiving most messages
2. Move them to the child's buffer

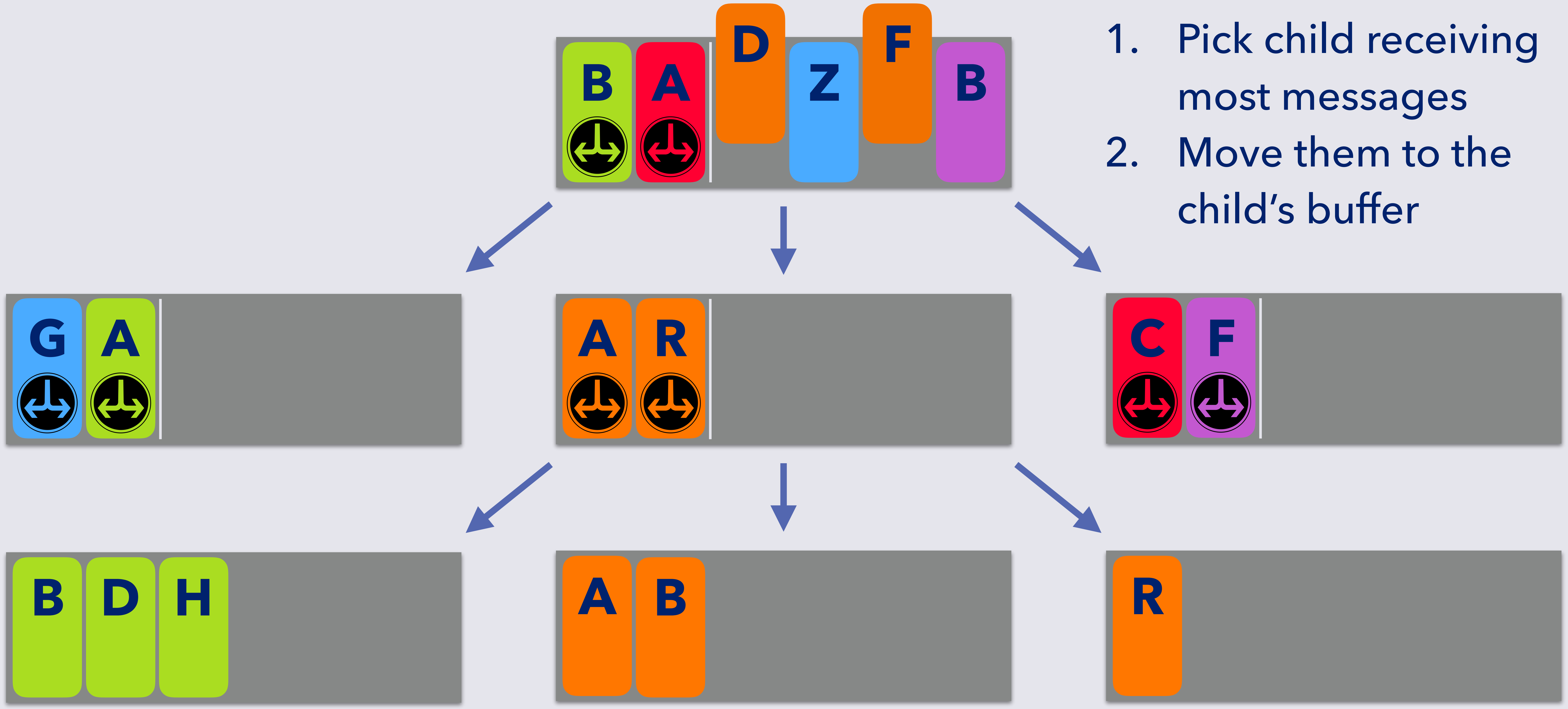




Bε-Trees



A Bε-tree is a search tree (like a B-tree)



Inserts get put in the root buffer

When a buffer is full:

1. Pick child receiving most messages
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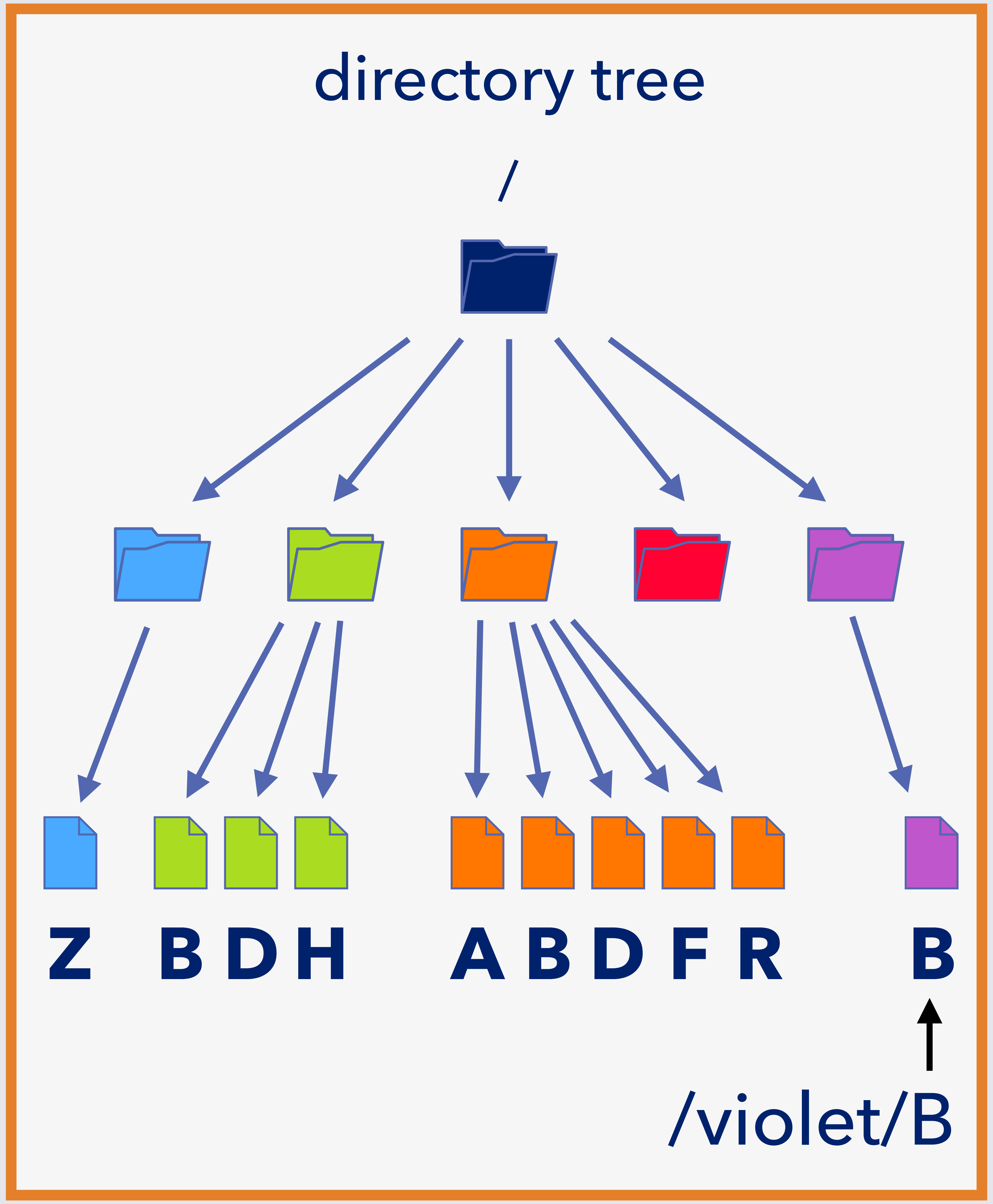
B$^{\varepsilon}$-Trees



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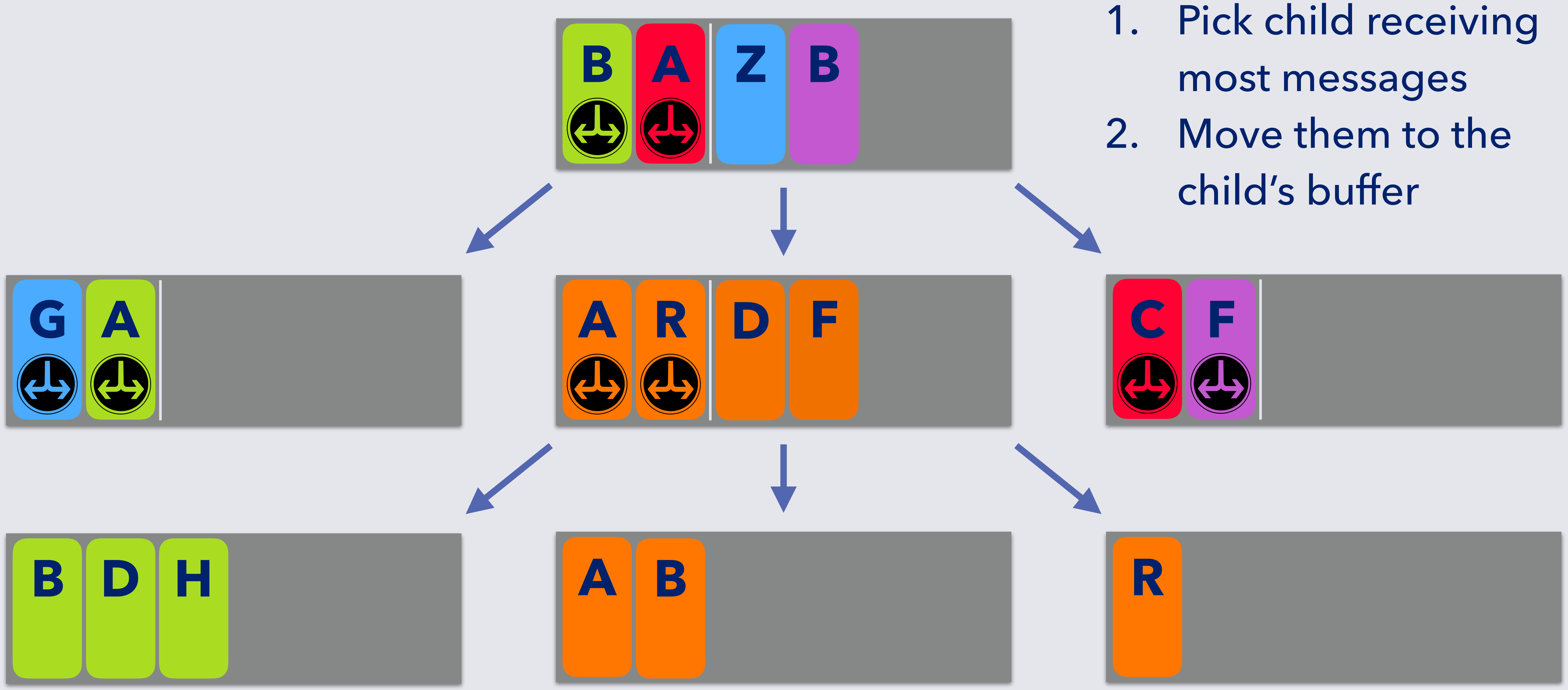

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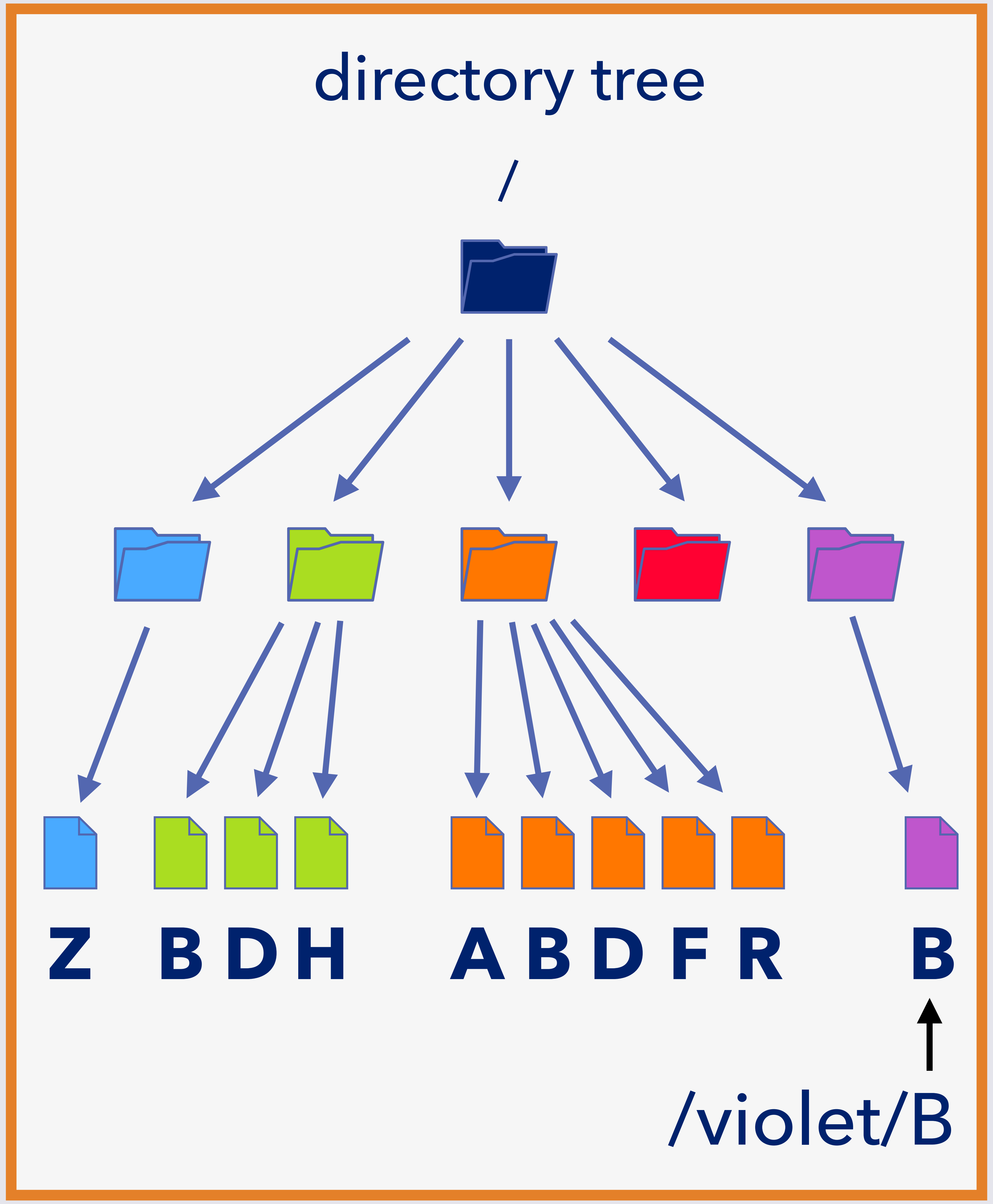
Bε-Trees



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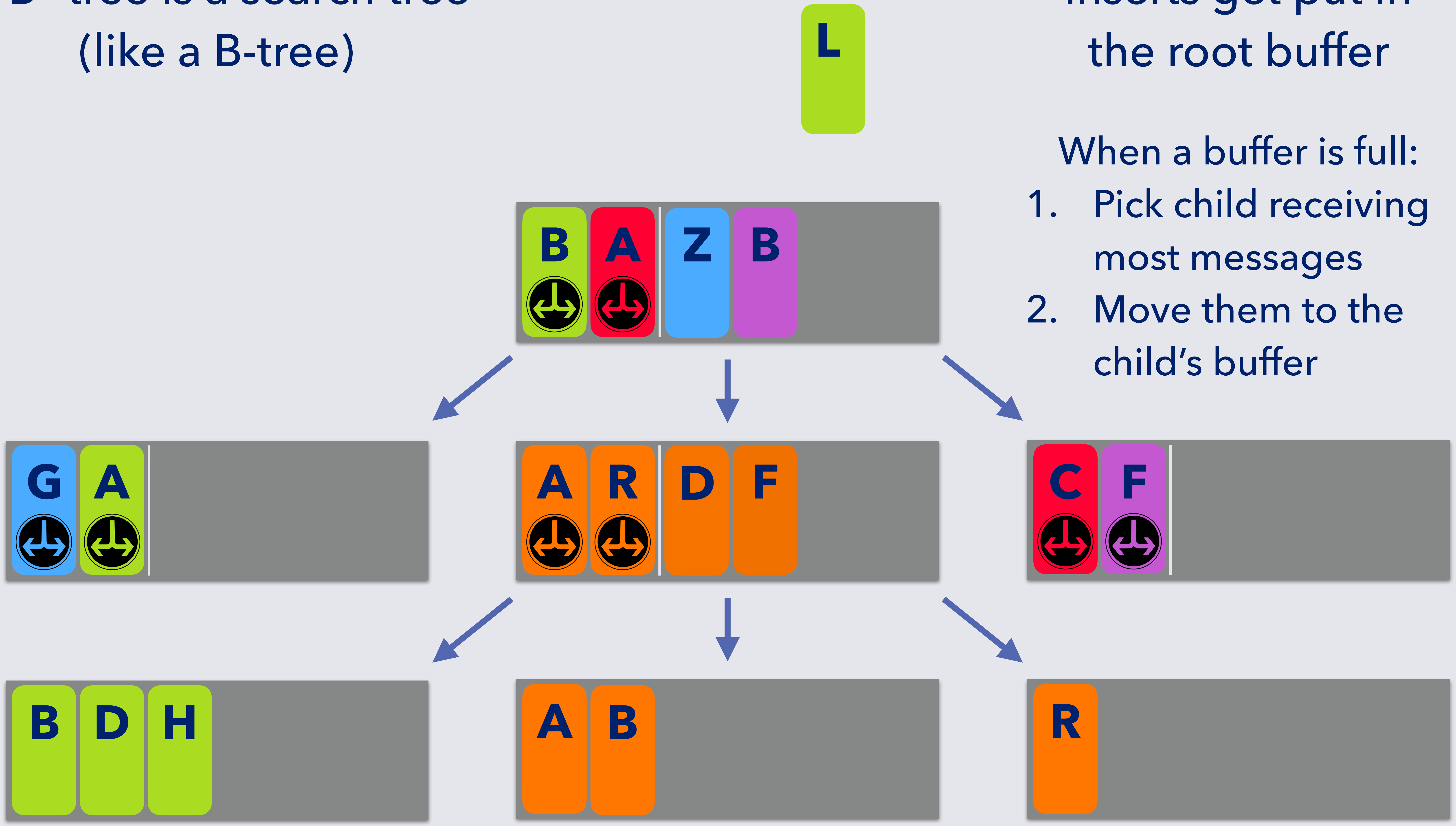

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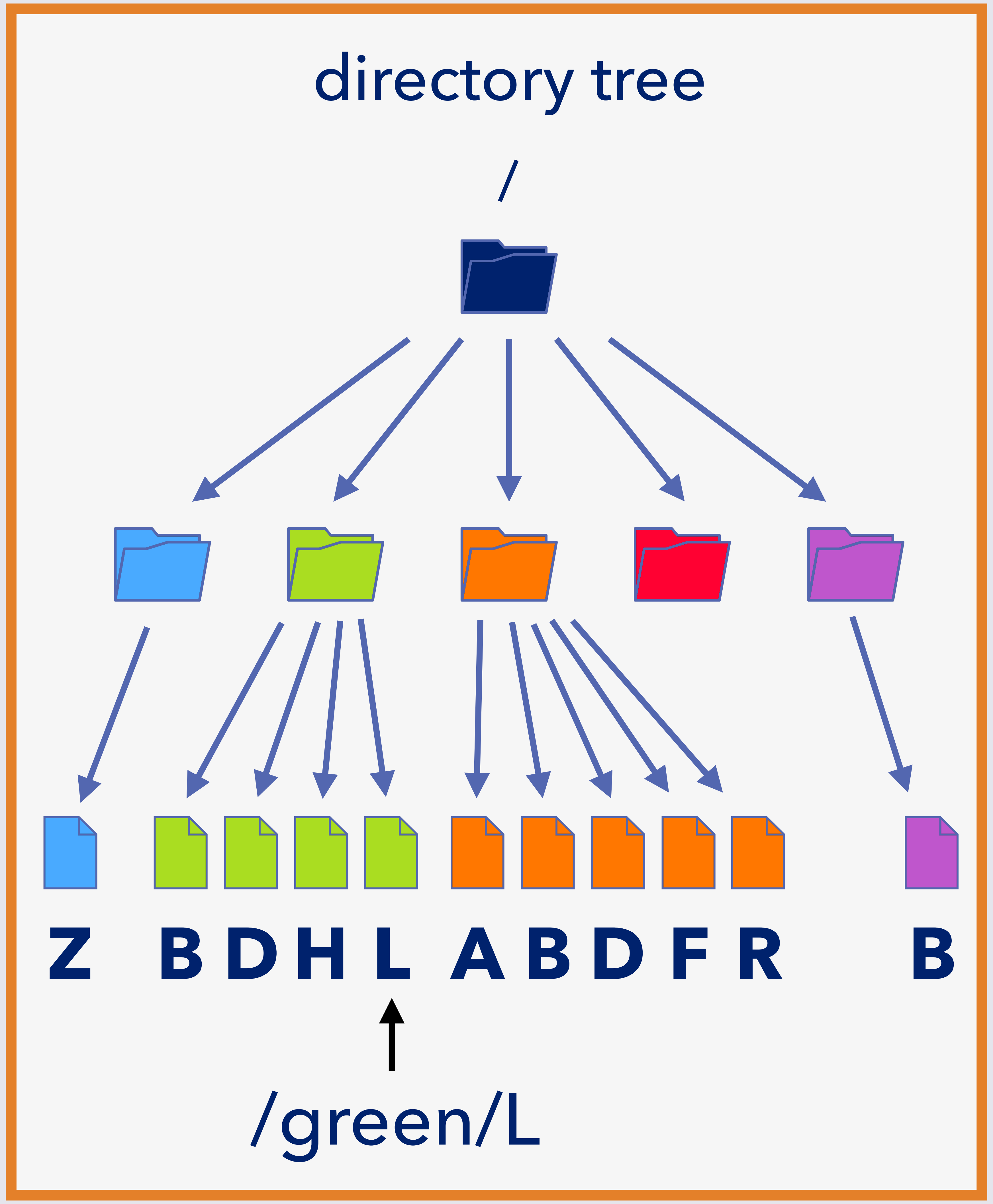
Bε-Trees



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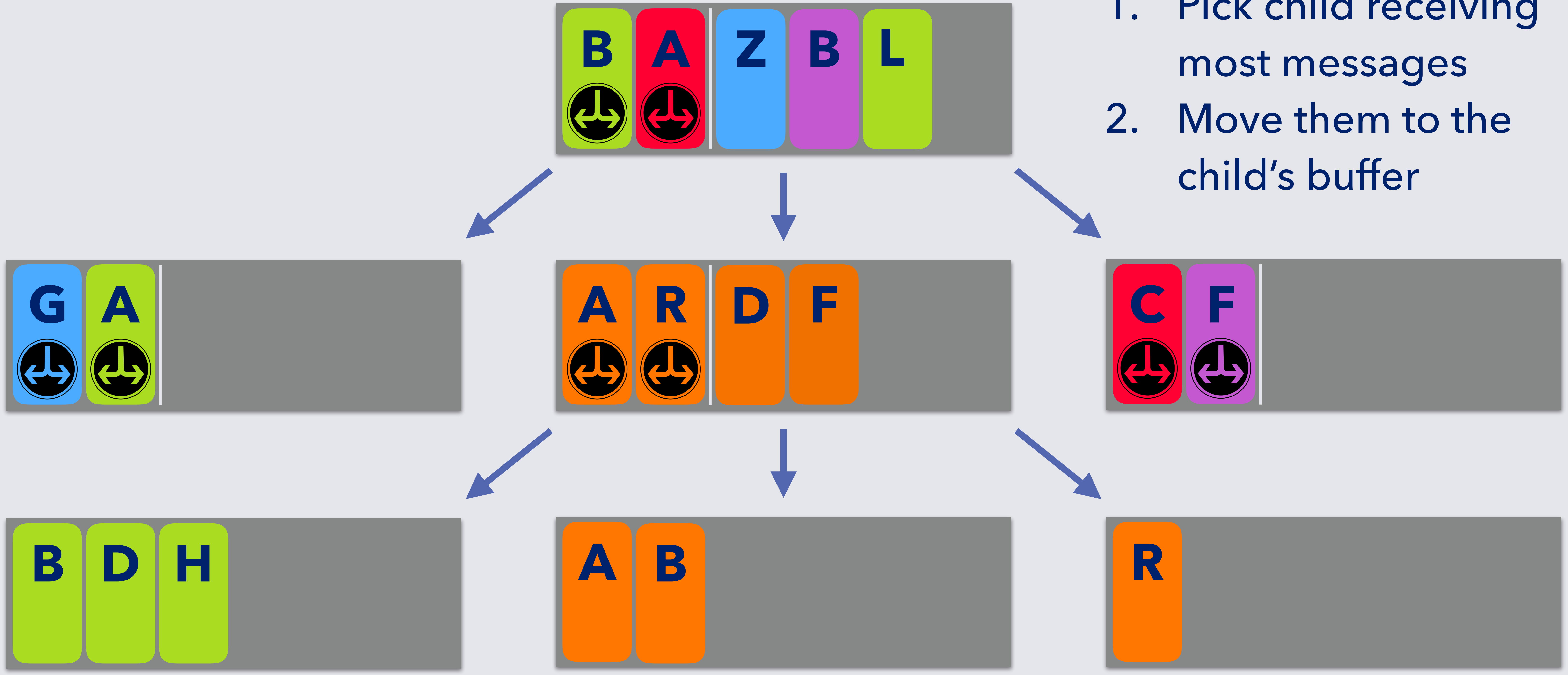

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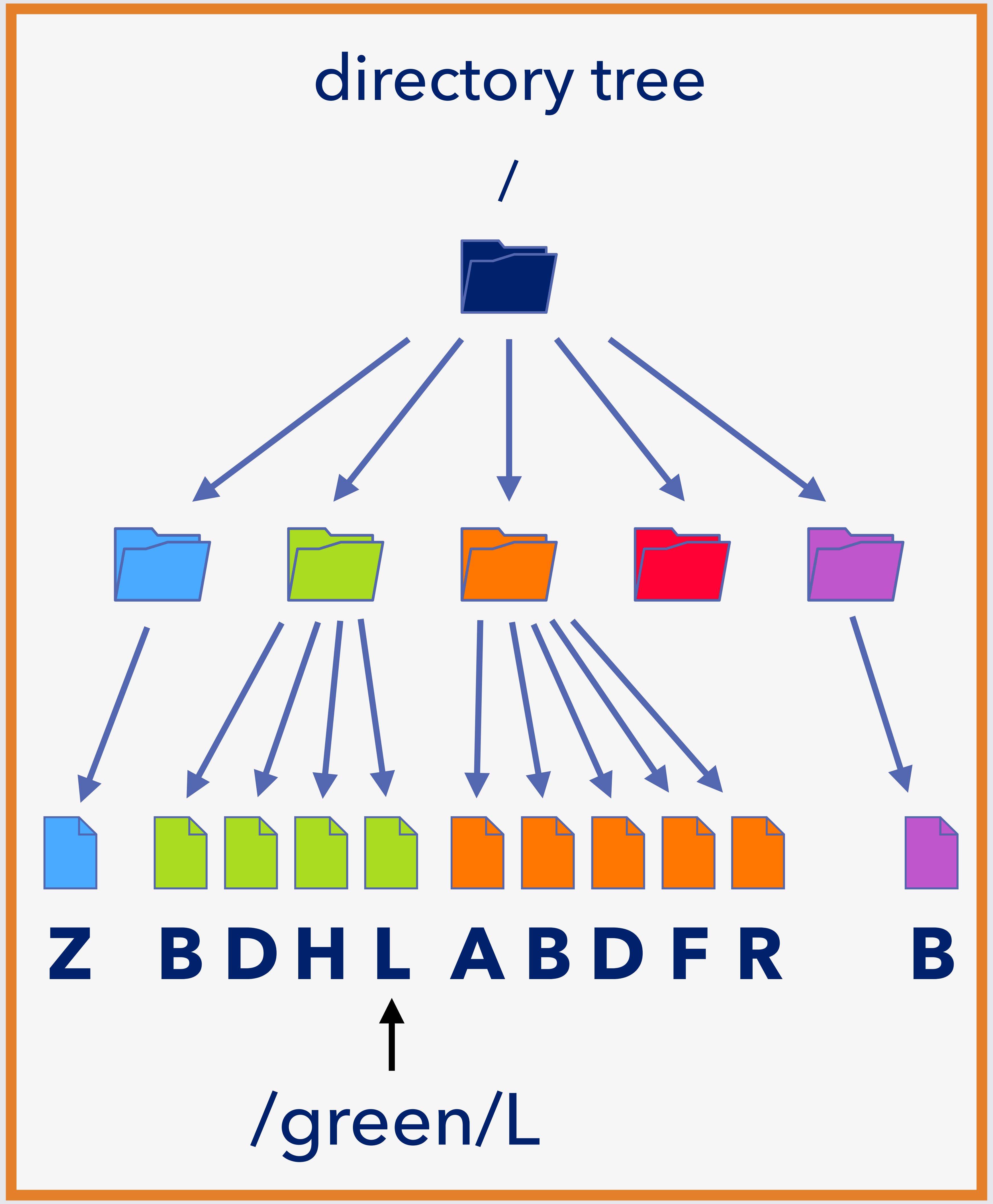
Bε-Trees



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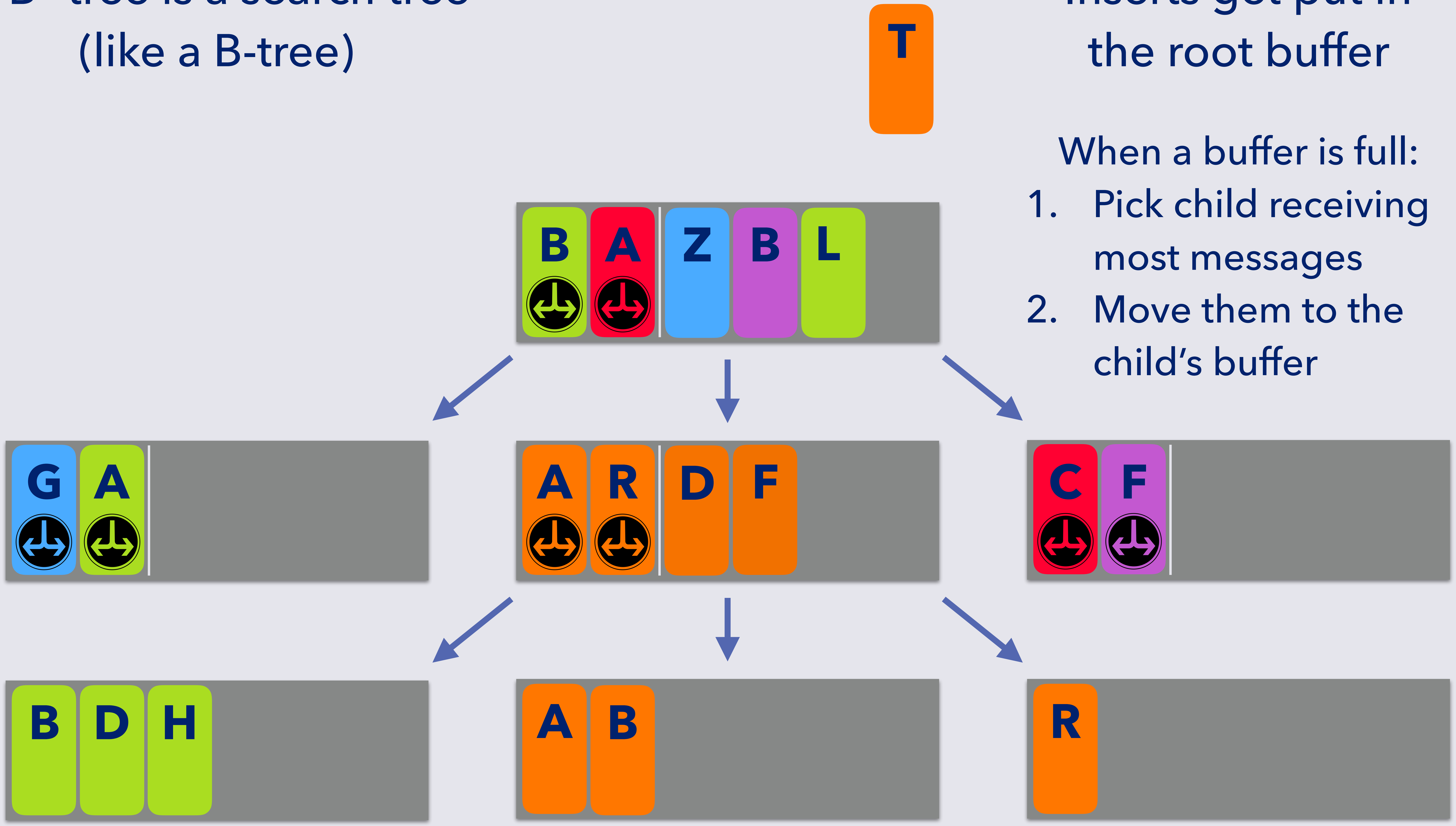

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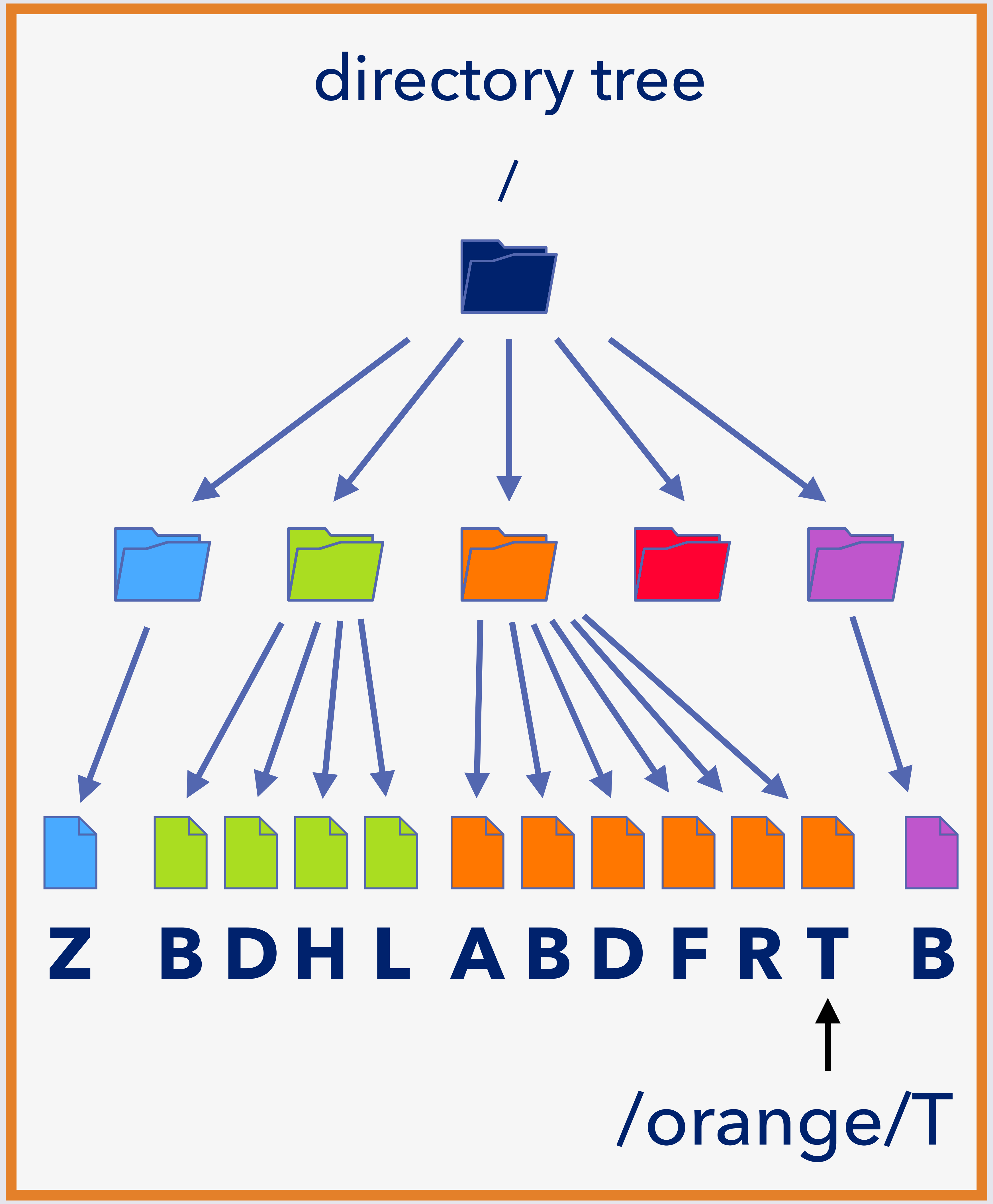
B$^{\varepsilon}$-Trees



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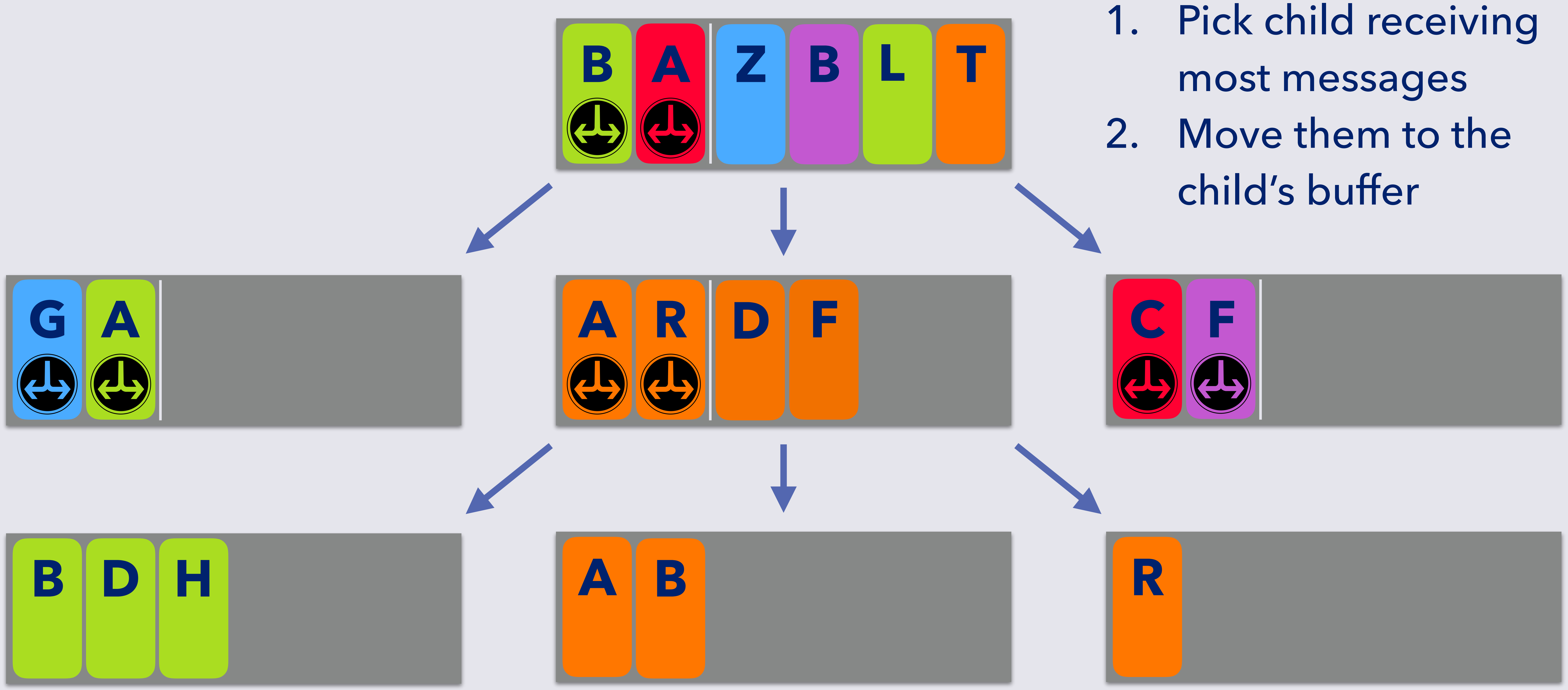

Inserts get put in
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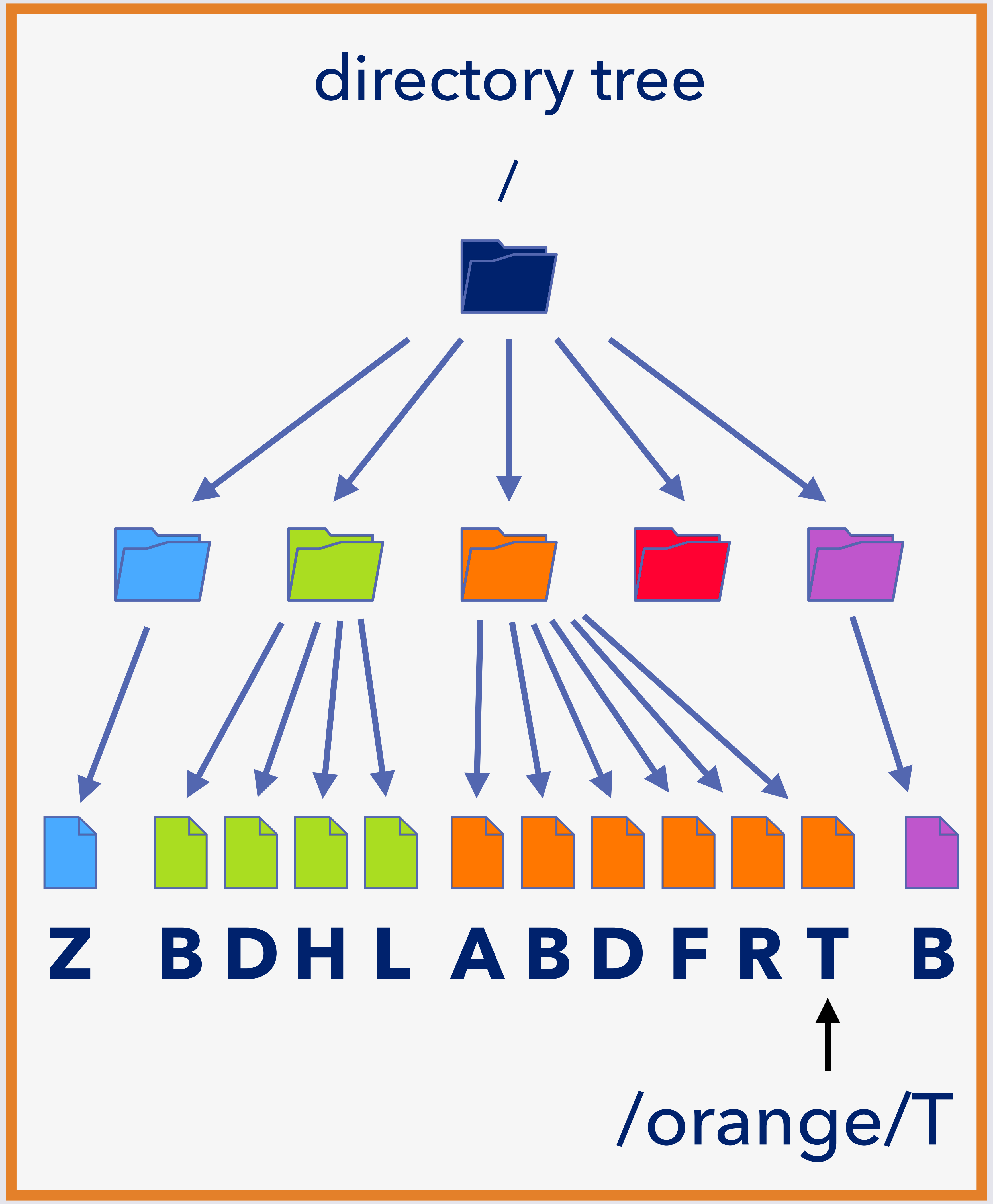
B$^{\varepsilon}$-Trees



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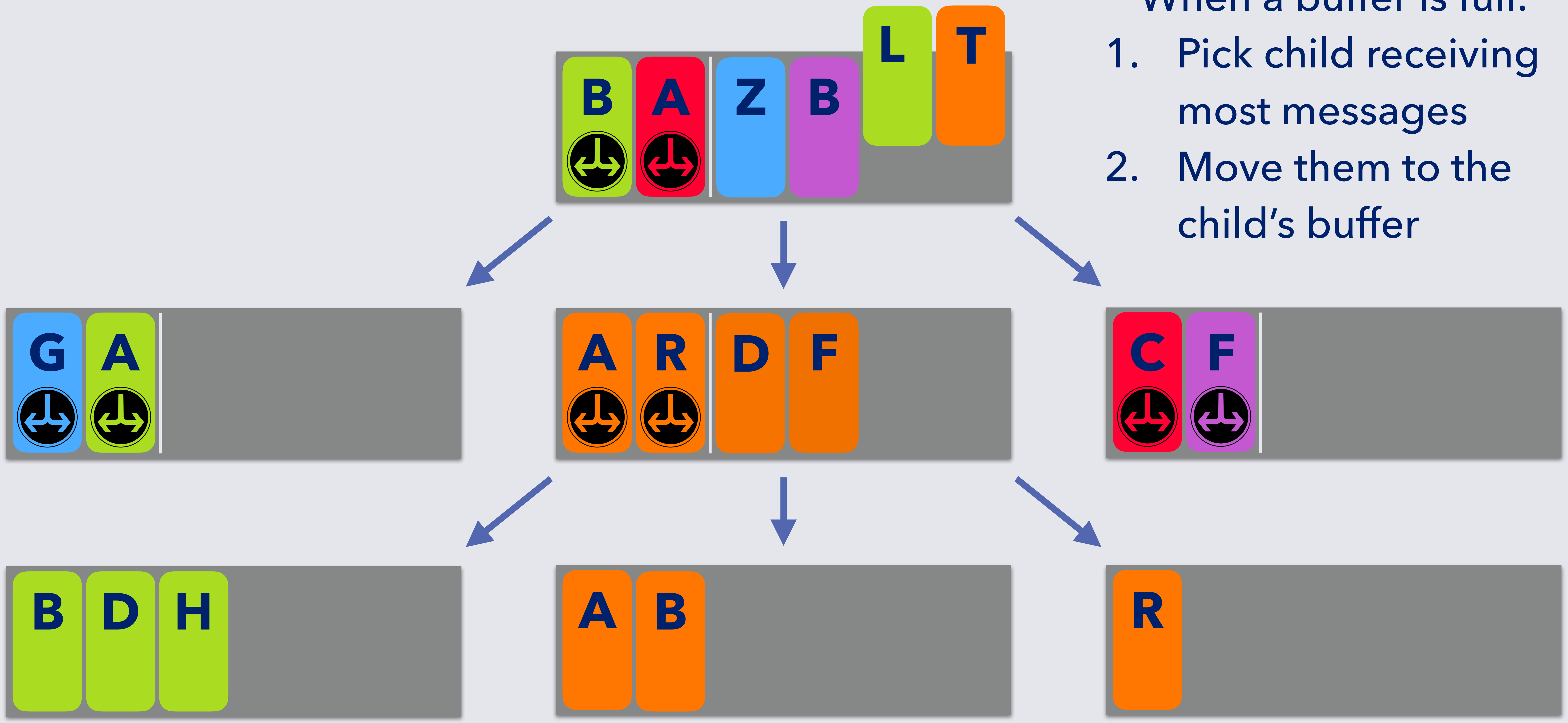
Inserts get put in the root buffer



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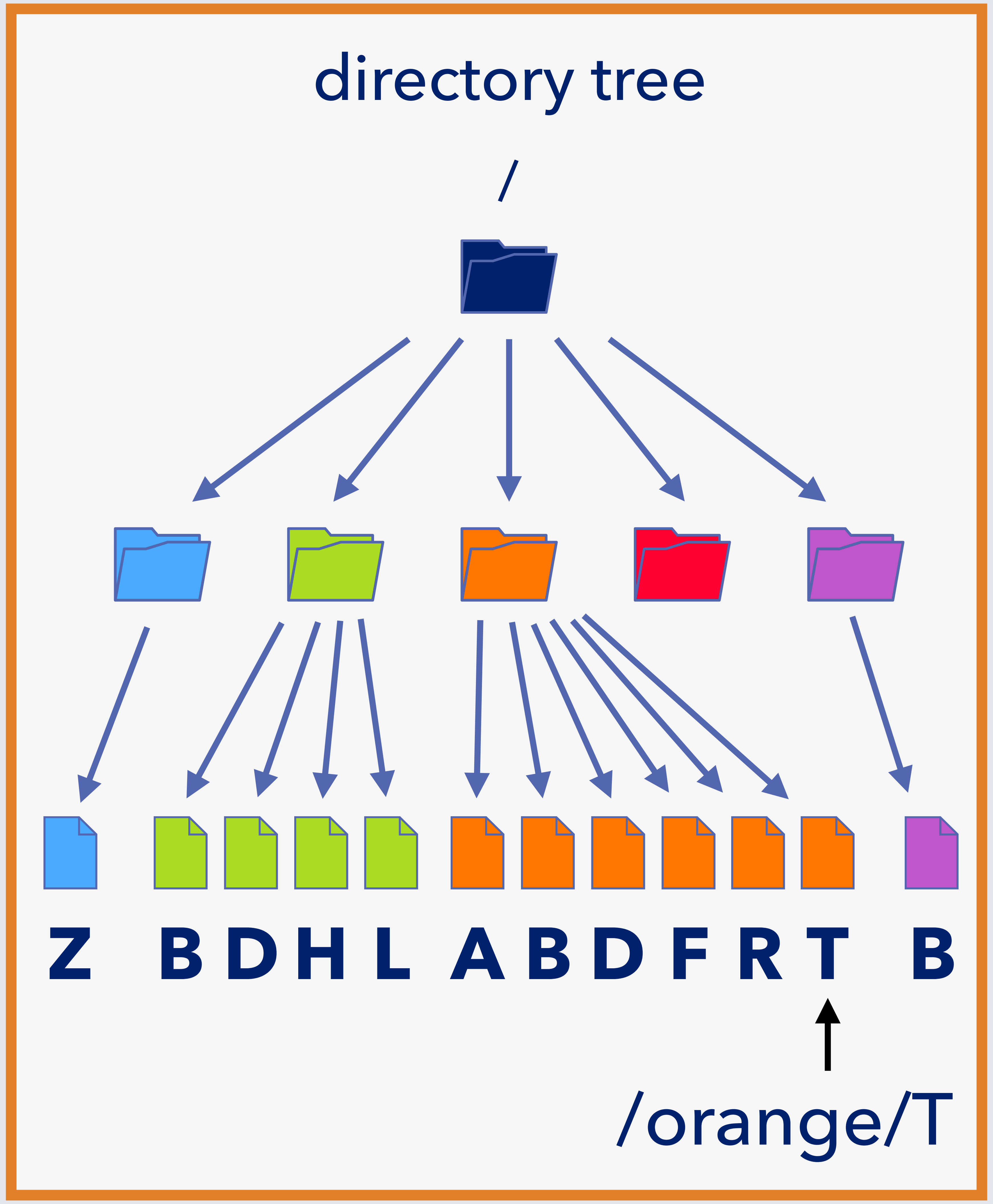
B^{ε}-Trees



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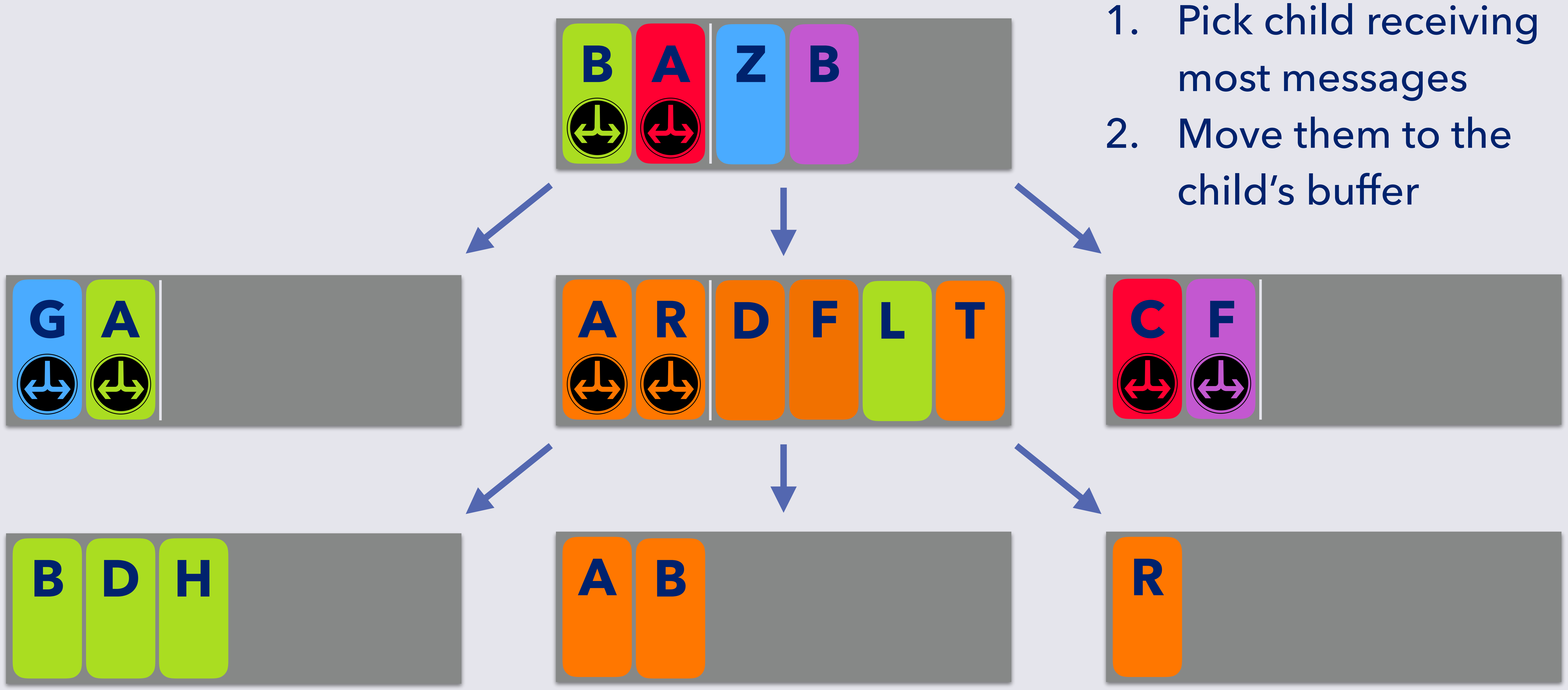

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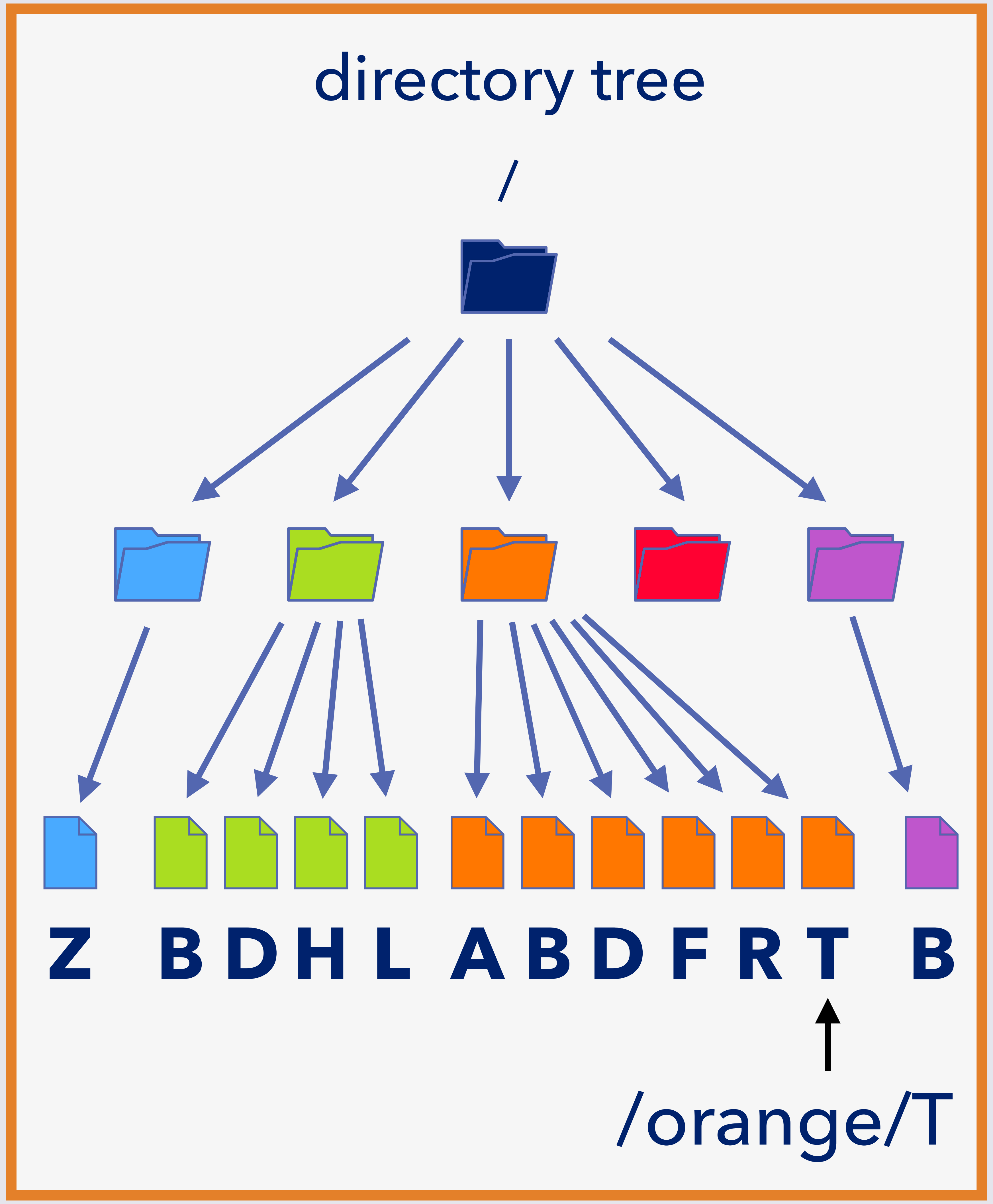
B$^{\varepsilon}$-Trees



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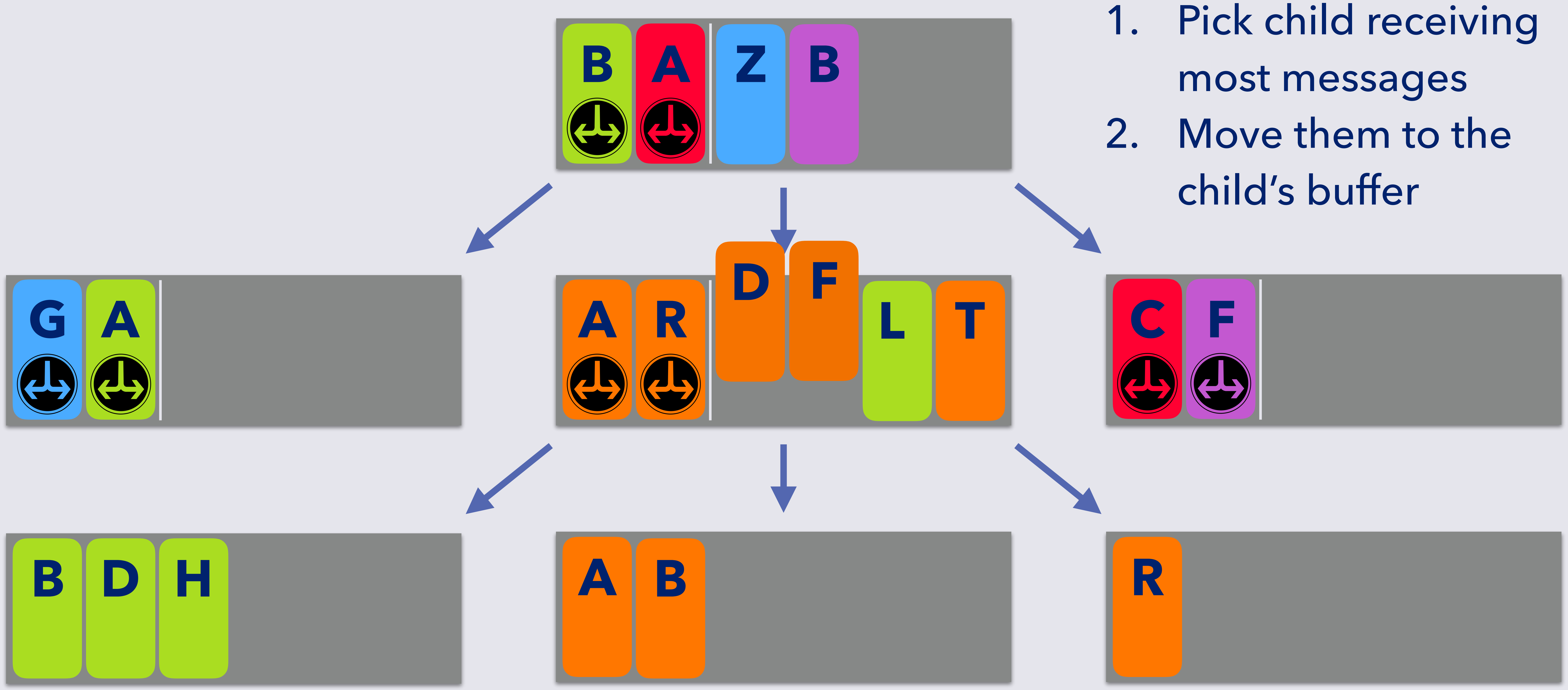

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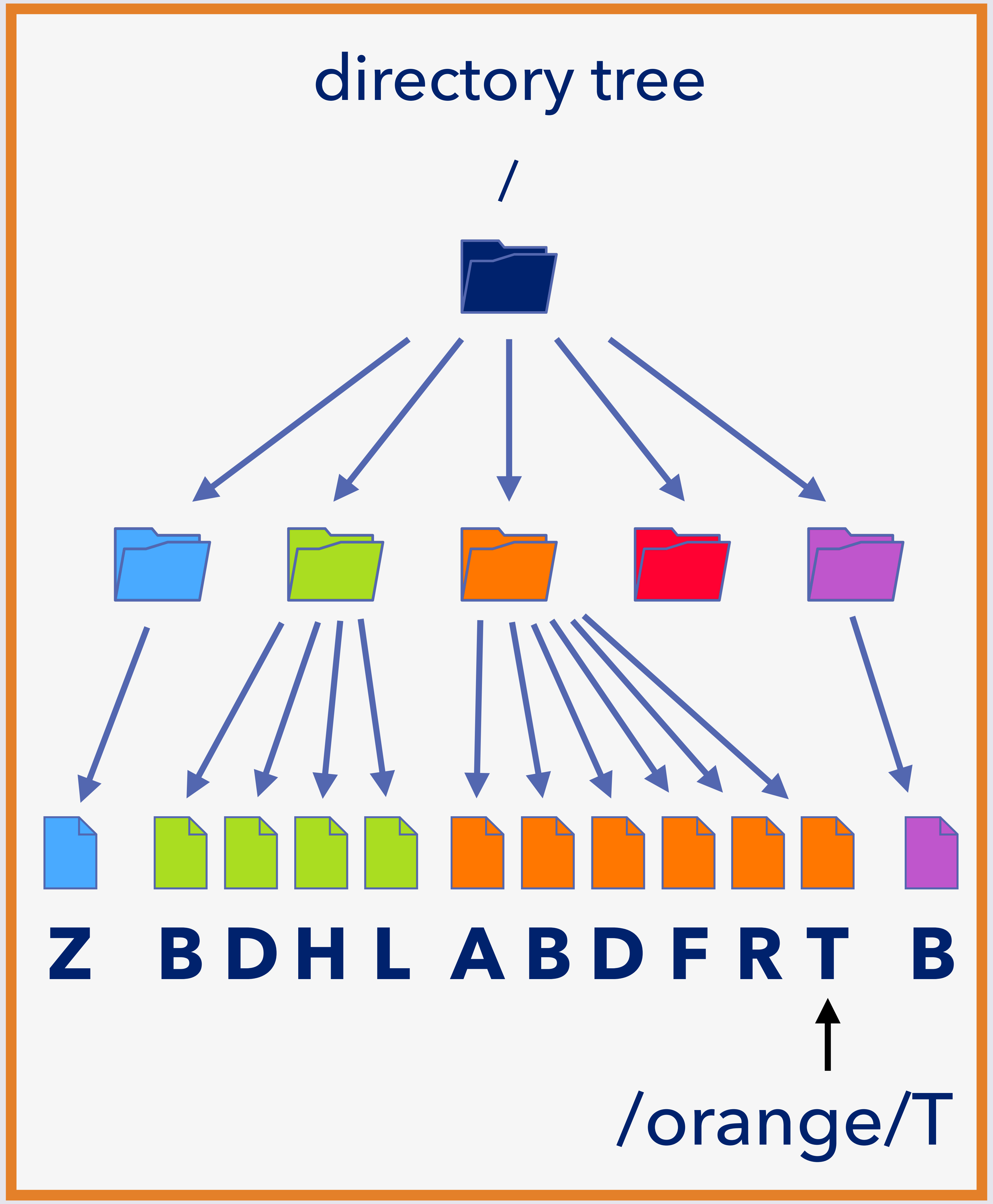

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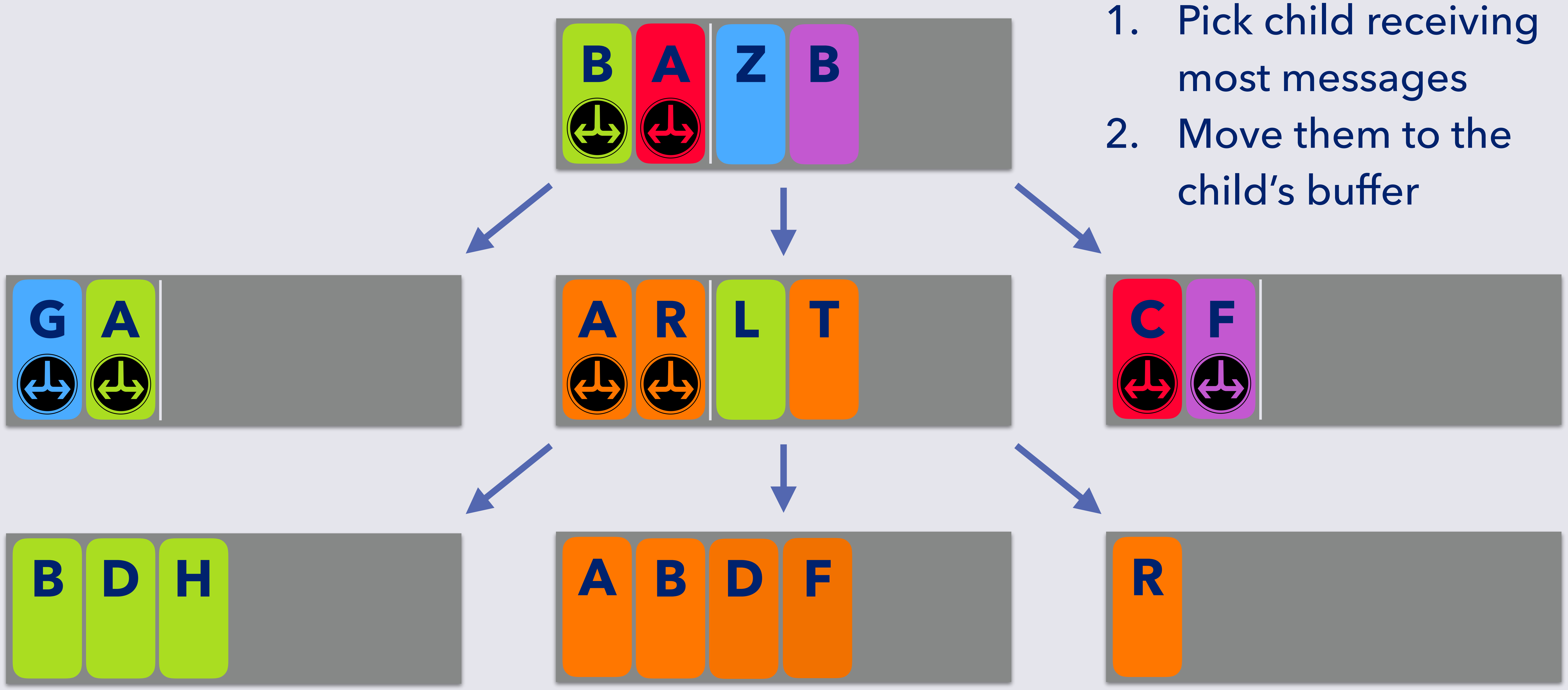

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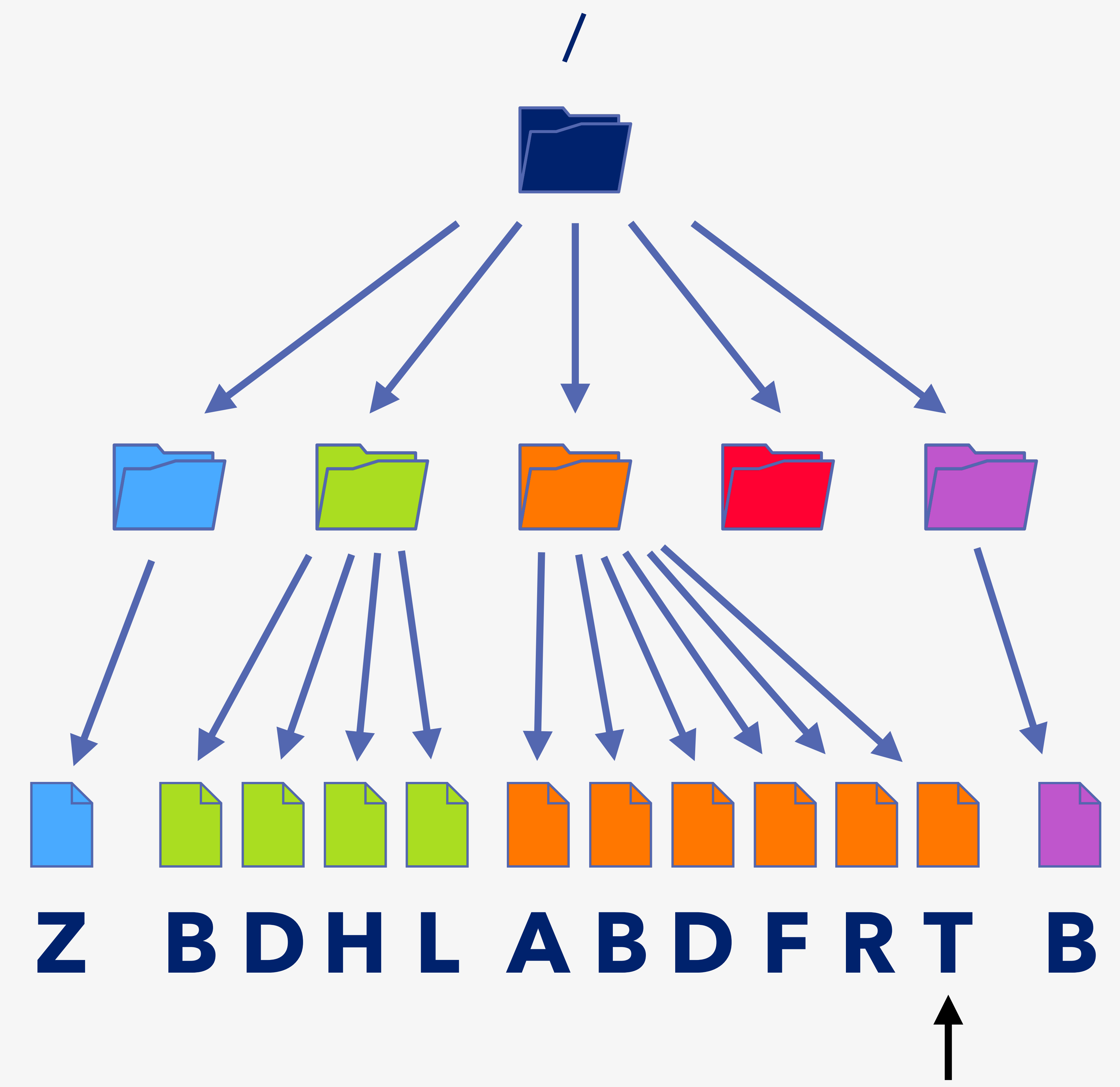
Bε-Trees



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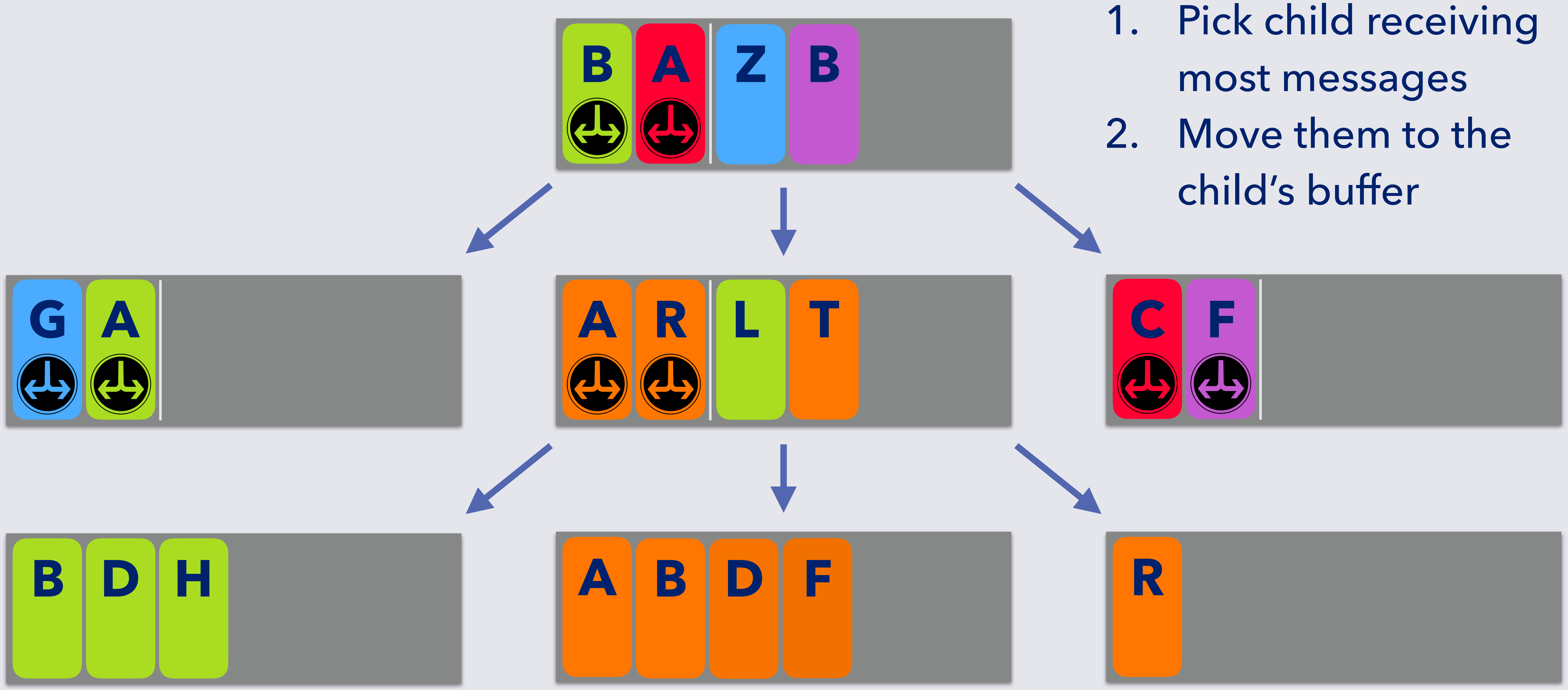

Inserts get put in the root buffer

When a buffer is full:

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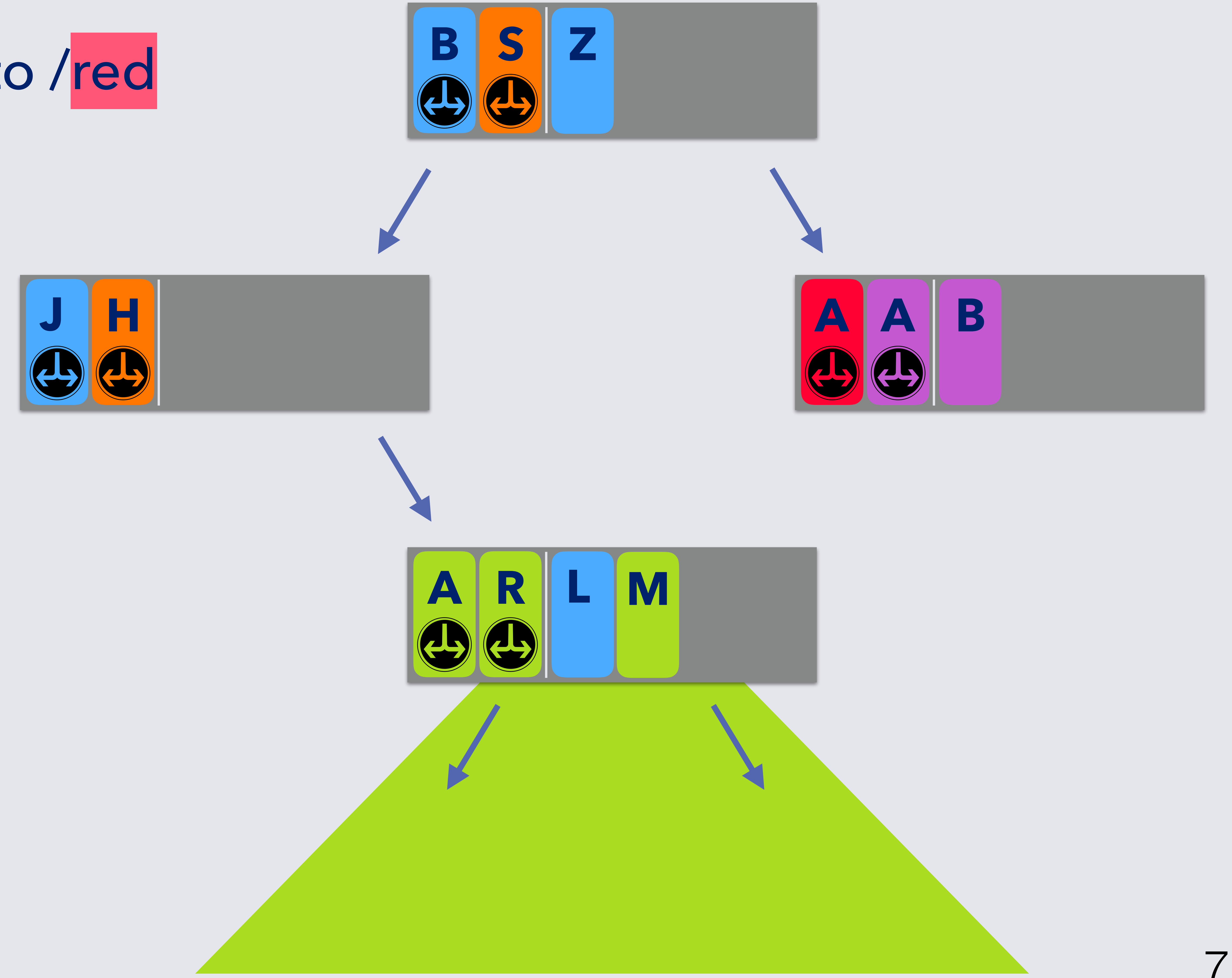
Key Insight: Each flush applies many small changes

Logical Copy with B$^{\varepsilon}$-DAGs

Logical Copy with Bε-DAGs

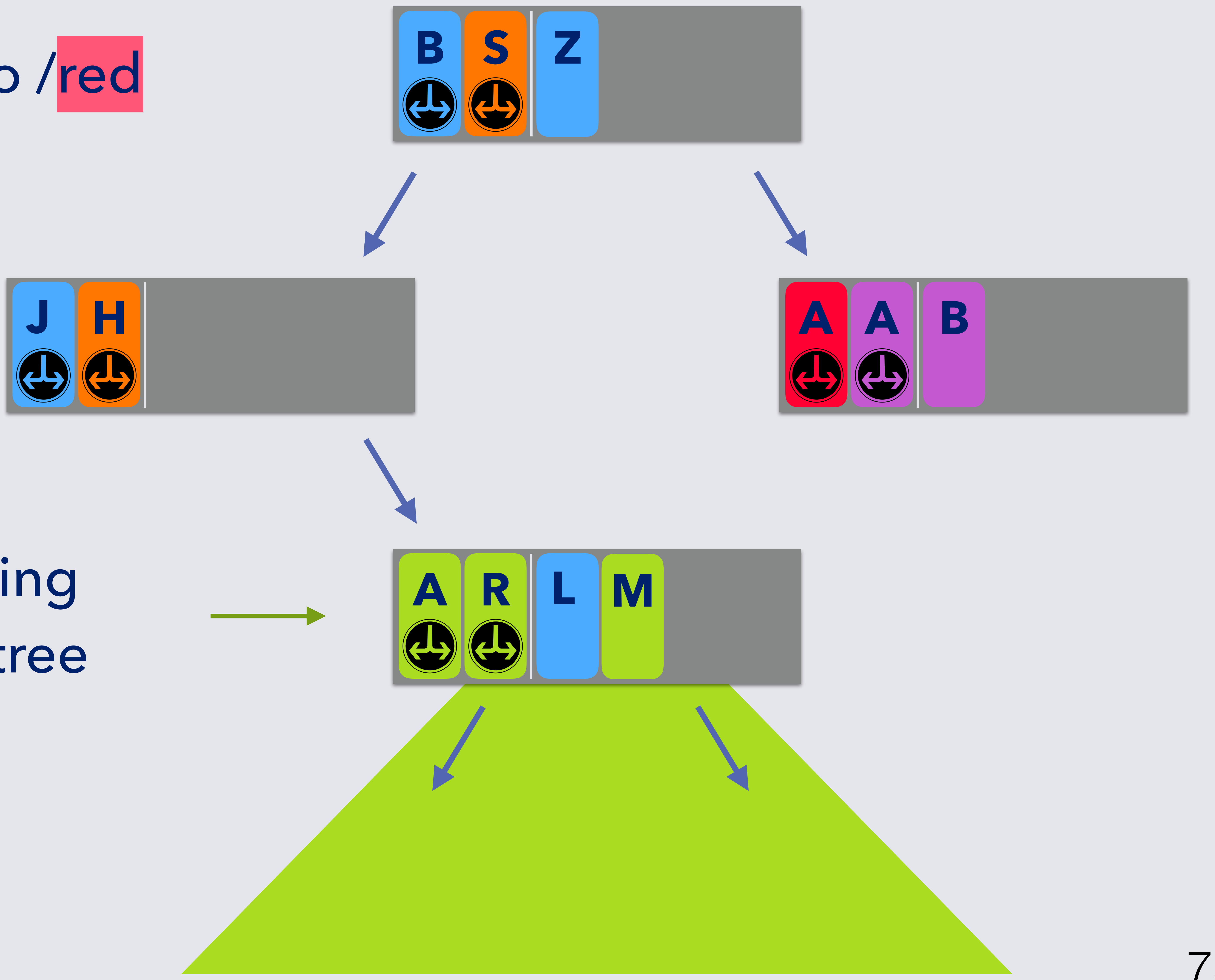
Copy /green to /red



Logical Copy with Bε-DAGs

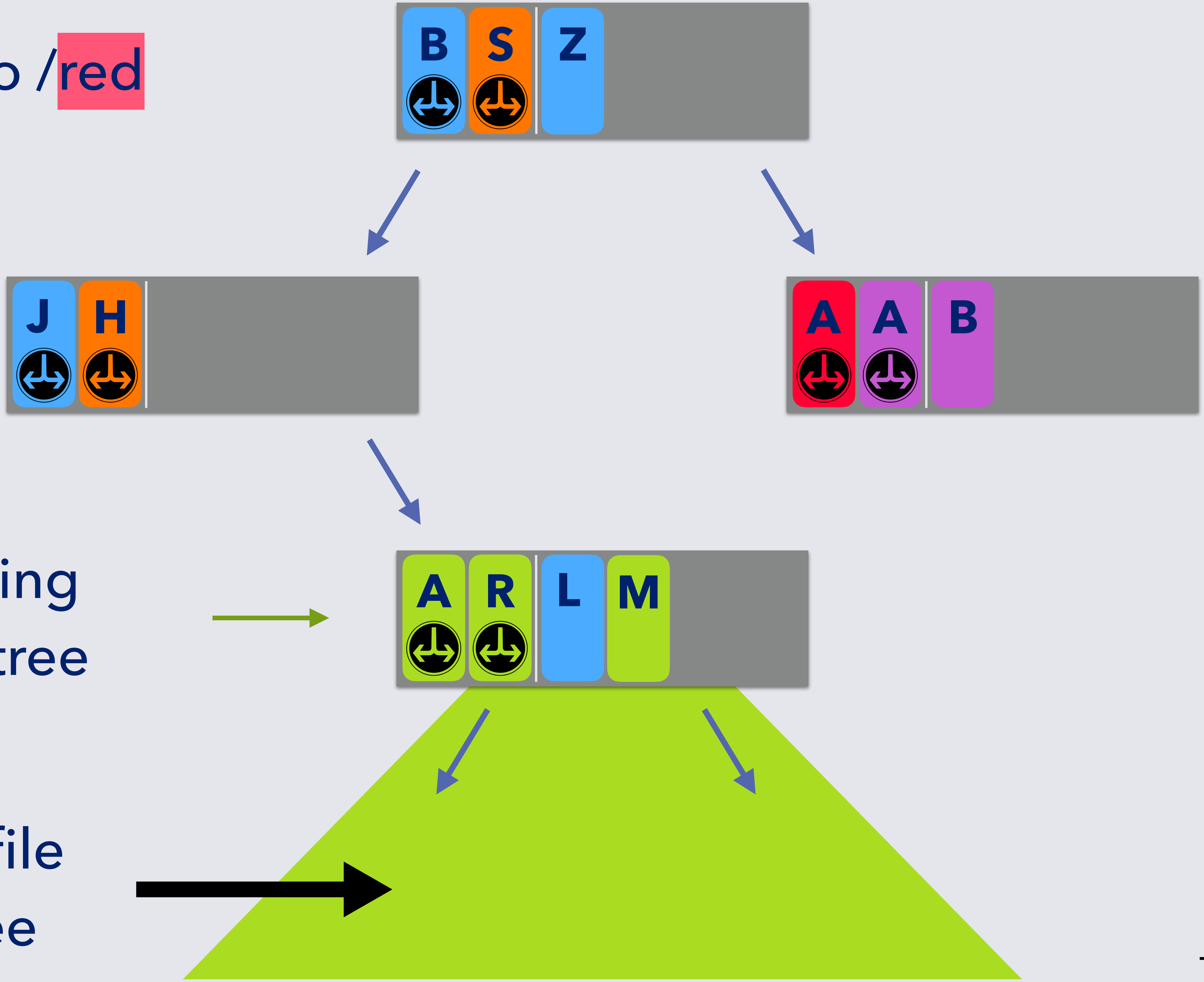
Copy /green to /red

Node covering /green/ subtree



Logical Copy with Bε-DAGs

Copy /green to /red



Node covering /green/ subtree

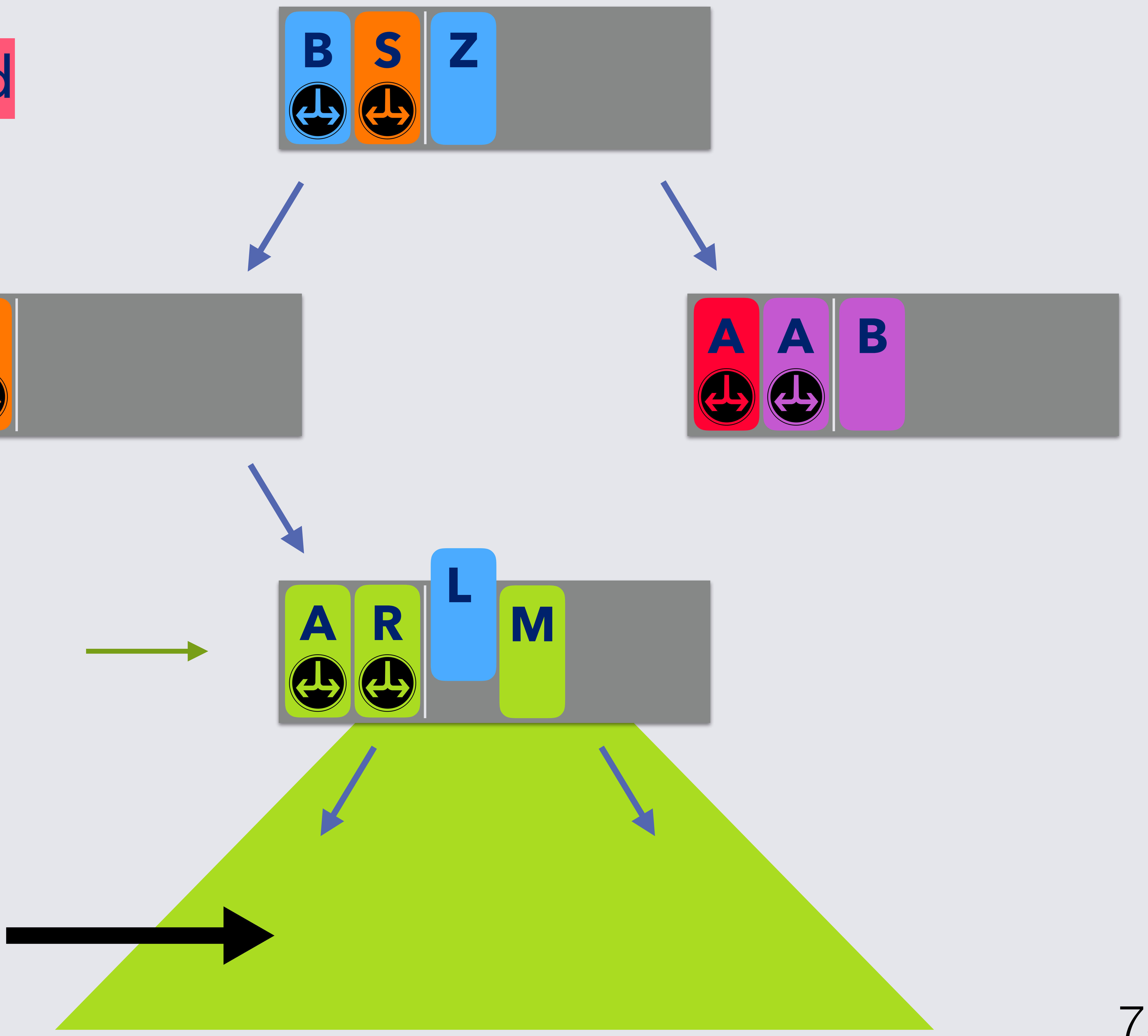
Every /green/* file is in this subtree

Logical Copy with Bε-DAGs

Copy /green to /red

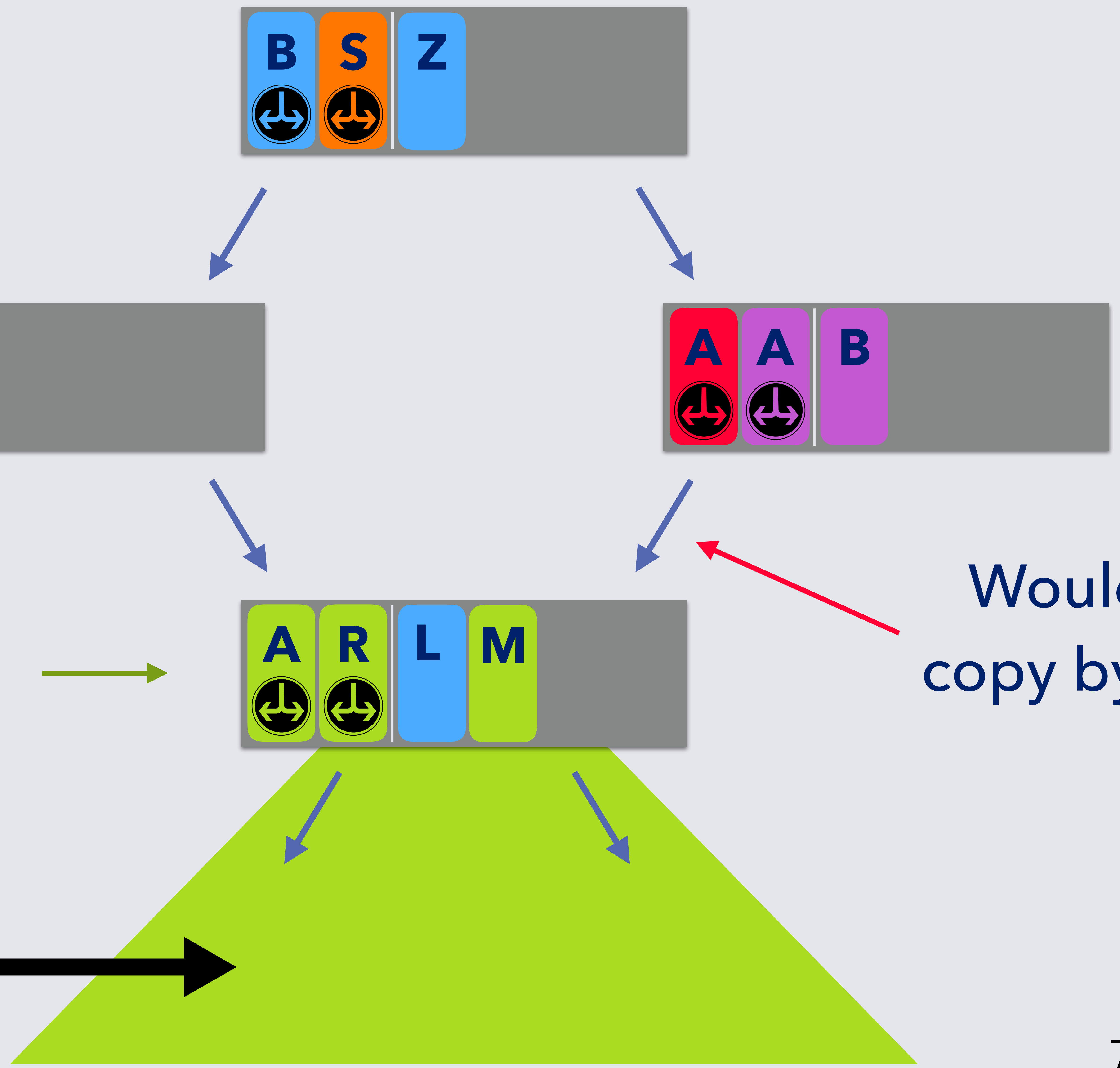
Node covering /green/ subtree

Every /green/* file is in this subtree



Logical Copy with Bε-DAGs

Copy /green to /red



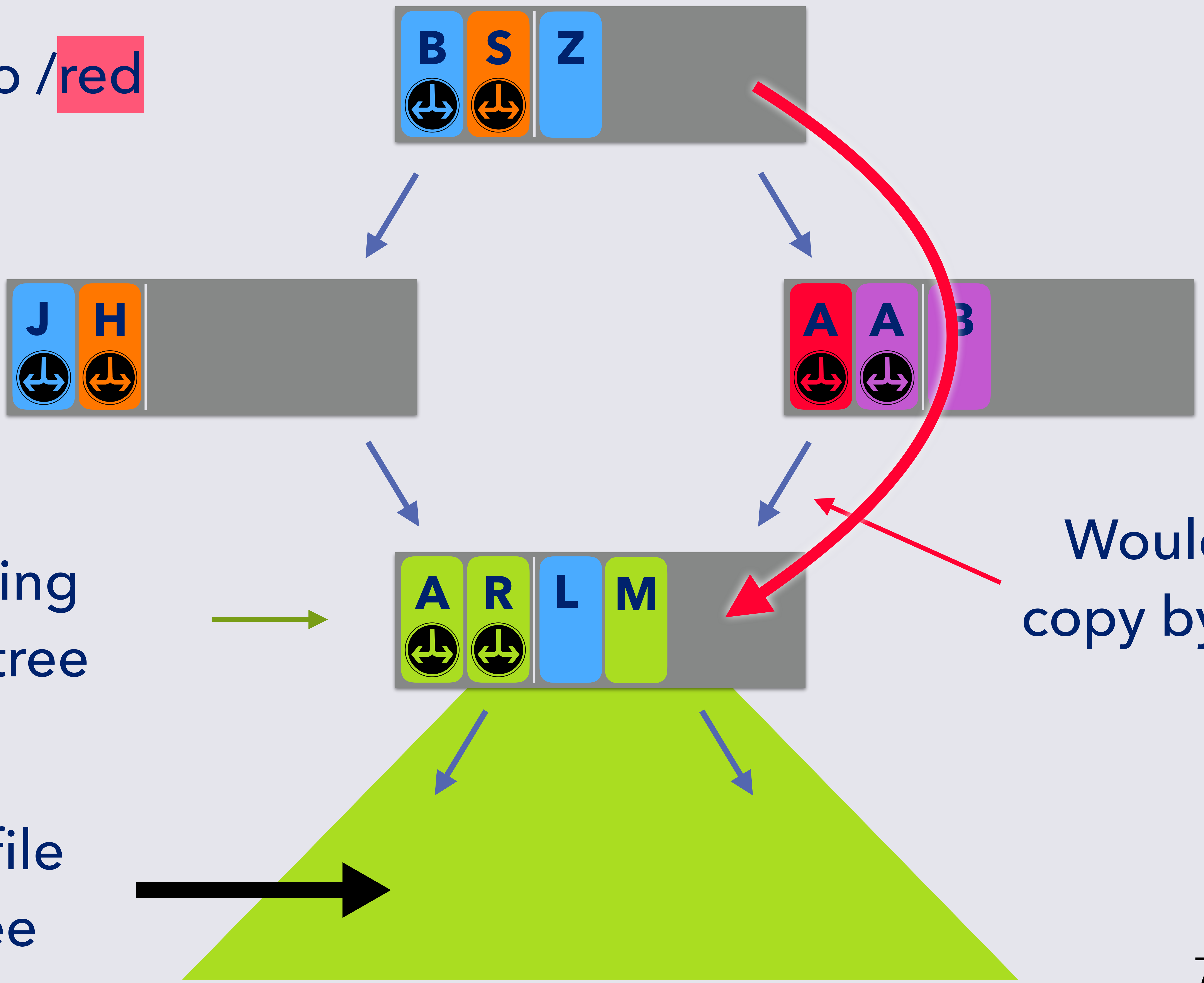
Node covering /green/ subtree

Would like to logically copy by adding this edge

Every /green/* file is in this subtree

Logical Copy with Bε-DAGs

Copy /green to /red



Node covering /green/ subtree

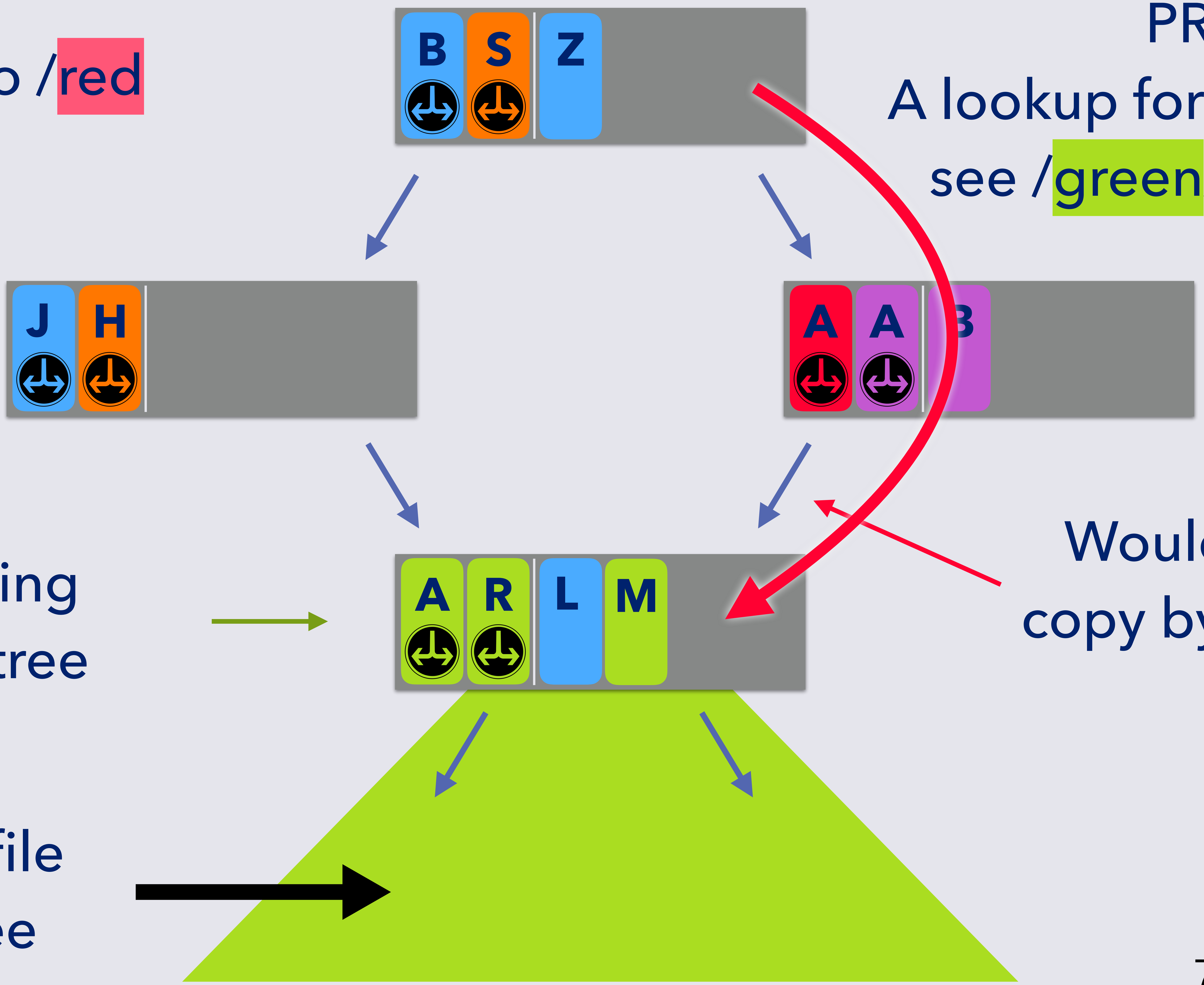
Every /green/* file is in this subtree

Would like to logically copy by adding this edge

Logical Copy with Bε-DAGs

Copy /green to /red

PROBLEM:
A lookup for /red/M is going to see /green/M in the subtree



Node covering /green/ subtree

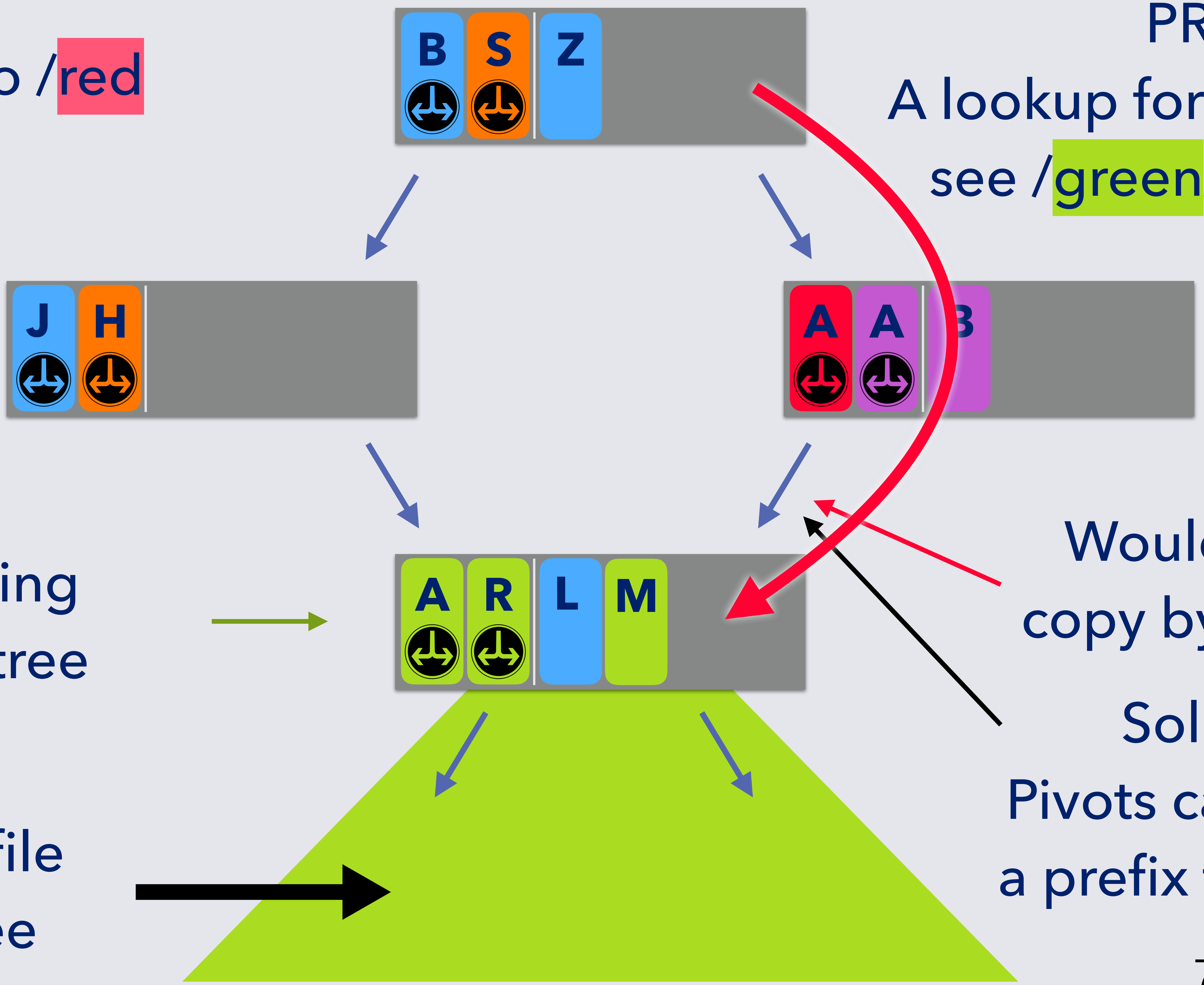
Would like to logically copy by adding this edge

Every /green/* file is in this subtree

Logical Copy with Bε-DAGs

Copy /green to /red

PROBLEM:
A lookup for /red/M is going to see /green/M in the subtree



Node covering /green/ subtree

Every /green/* file is in this subtree

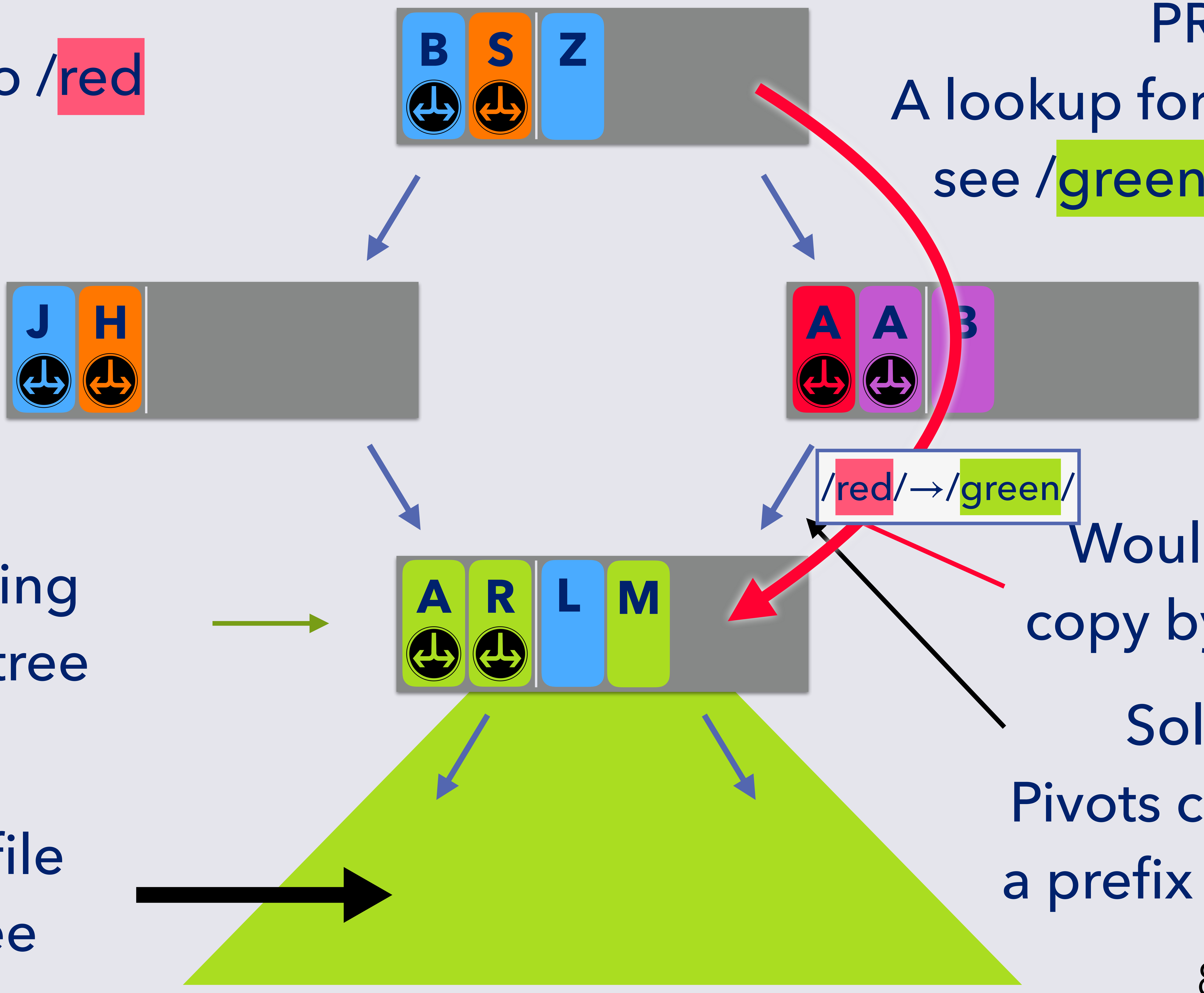
Would like to logically copy by adding this edge

Solution:
Pivots can include a prefix translation

Logical Copy with Bε-DAGs

Copy /green to /red

PROBLEM:
A lookup for /red/M is going to see /green/M in the subtree



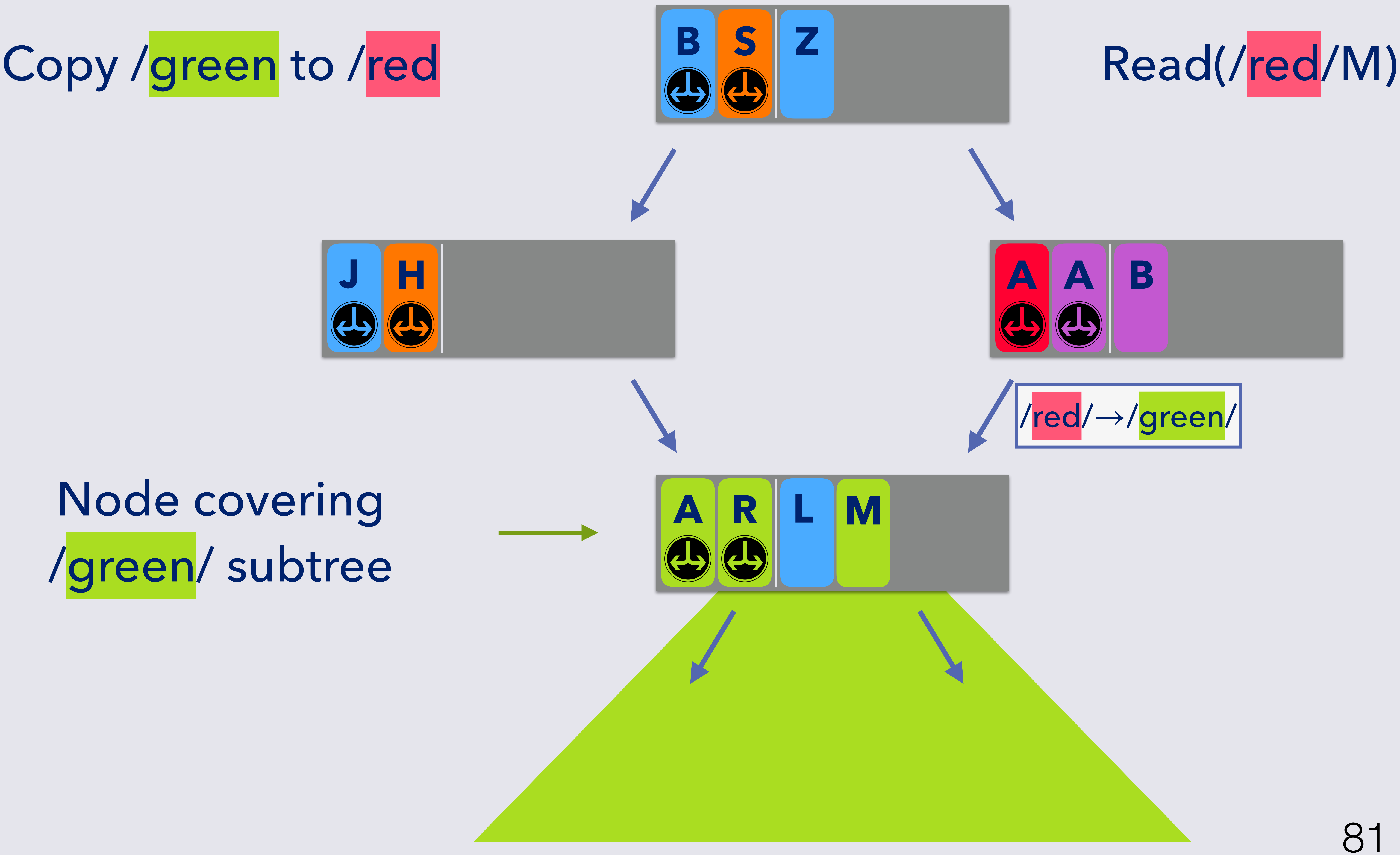
Node covering /green/ subtree

Would like to logically copy by adding this edge

Every /green/* file is in this subtree

Solution:
Pivots can include a prefix translation

Logical Copy with Bε-DAGs

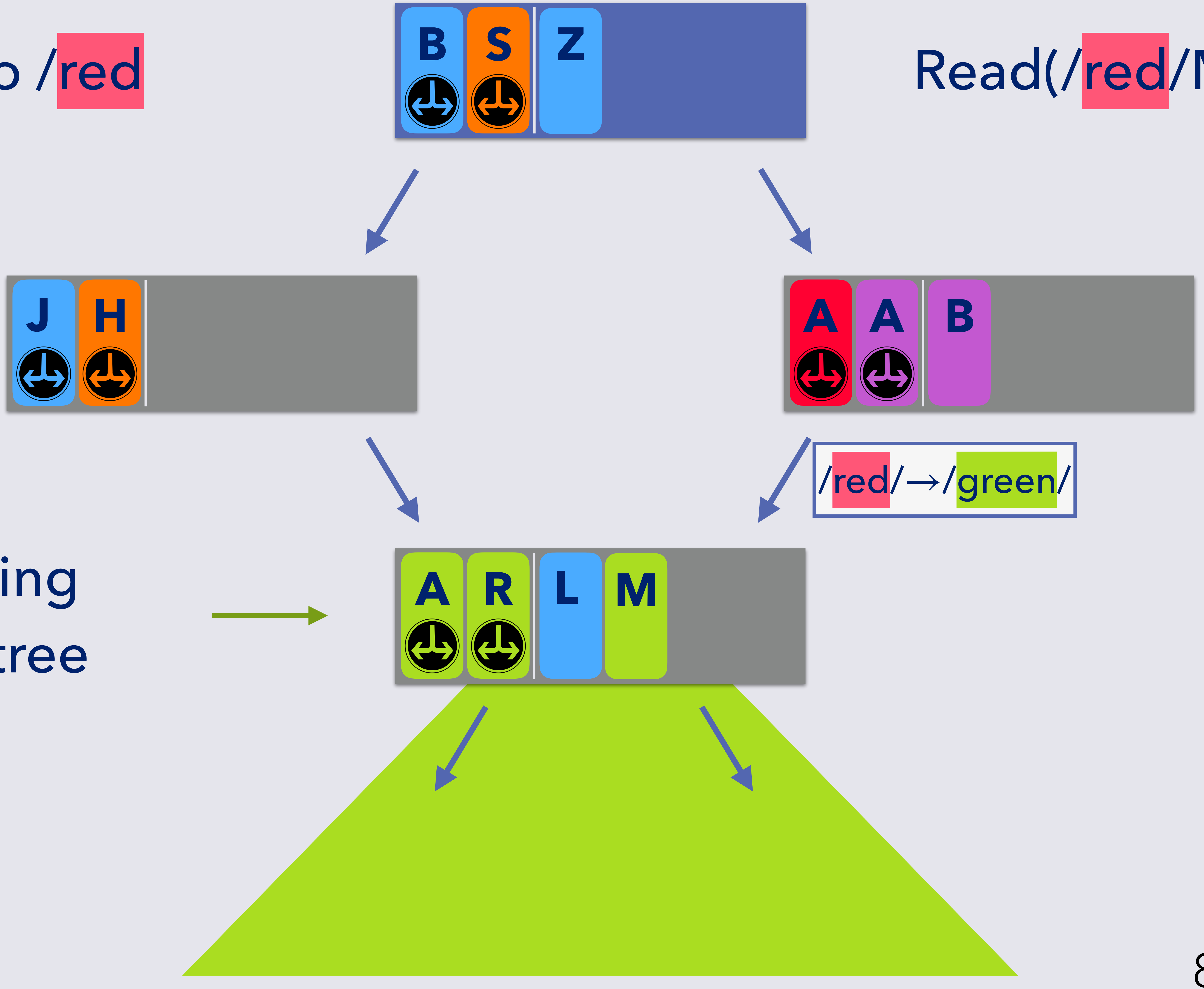


Logical Copy with Bε-DAGs

Copy /green to /red

Read(/red/M)

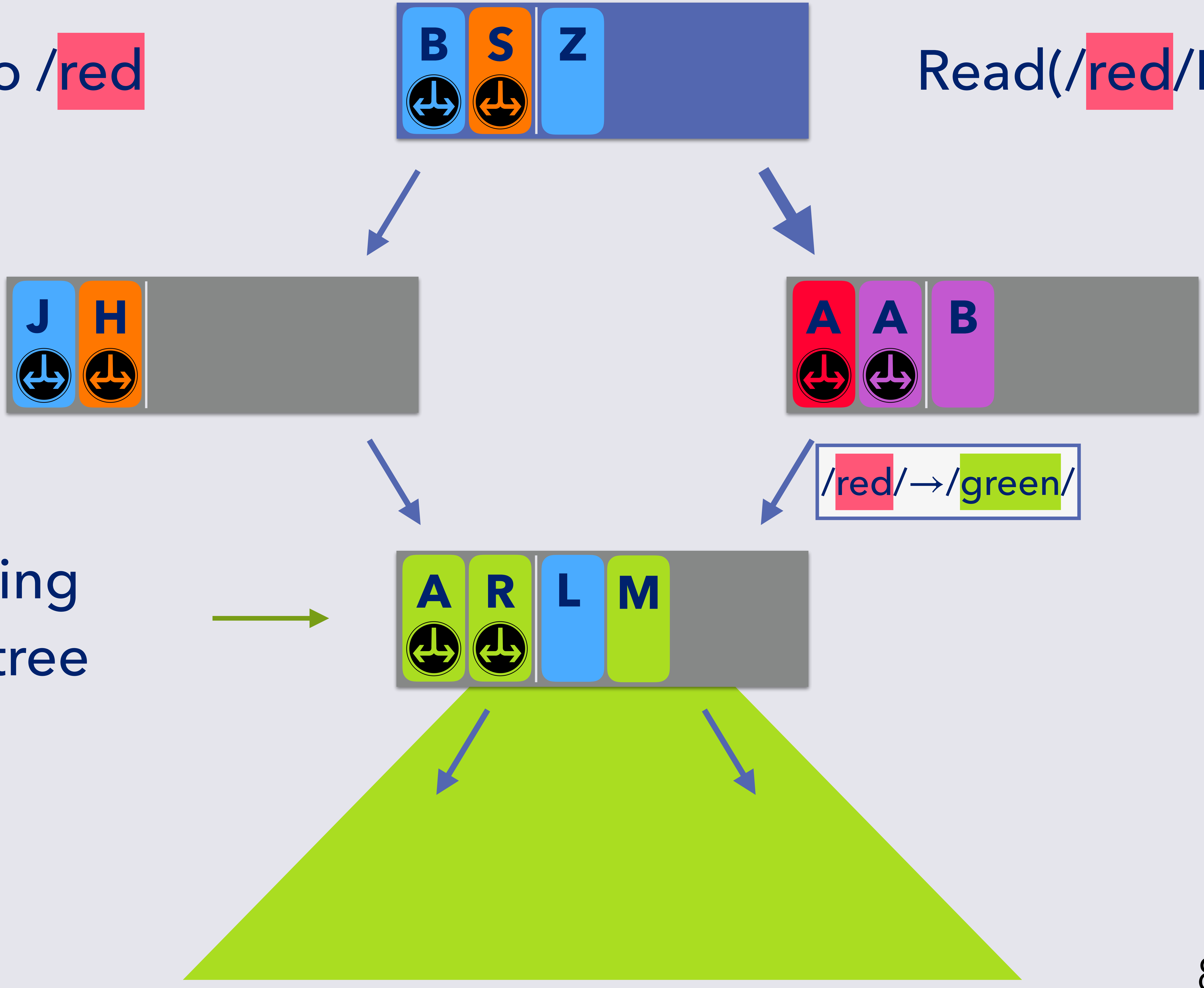
Node covering /green/ subtree



Logical Copy with Bε-DAGs

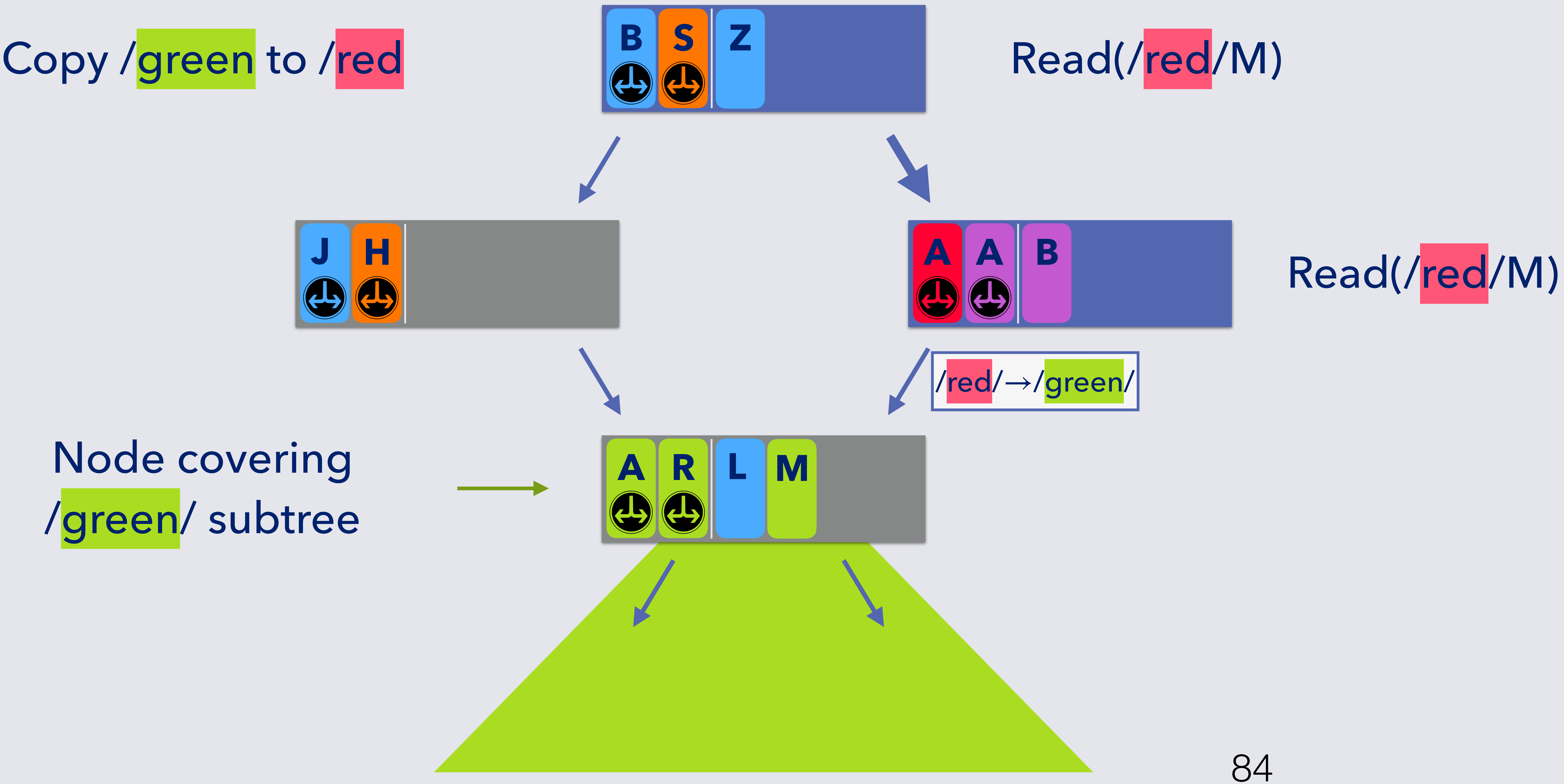
Copy /green to /red

Read(/red/M)



Node covering /green/ subtree

Logical Copy with Bε-DAGs



Logical Copy with Bε-DAGs

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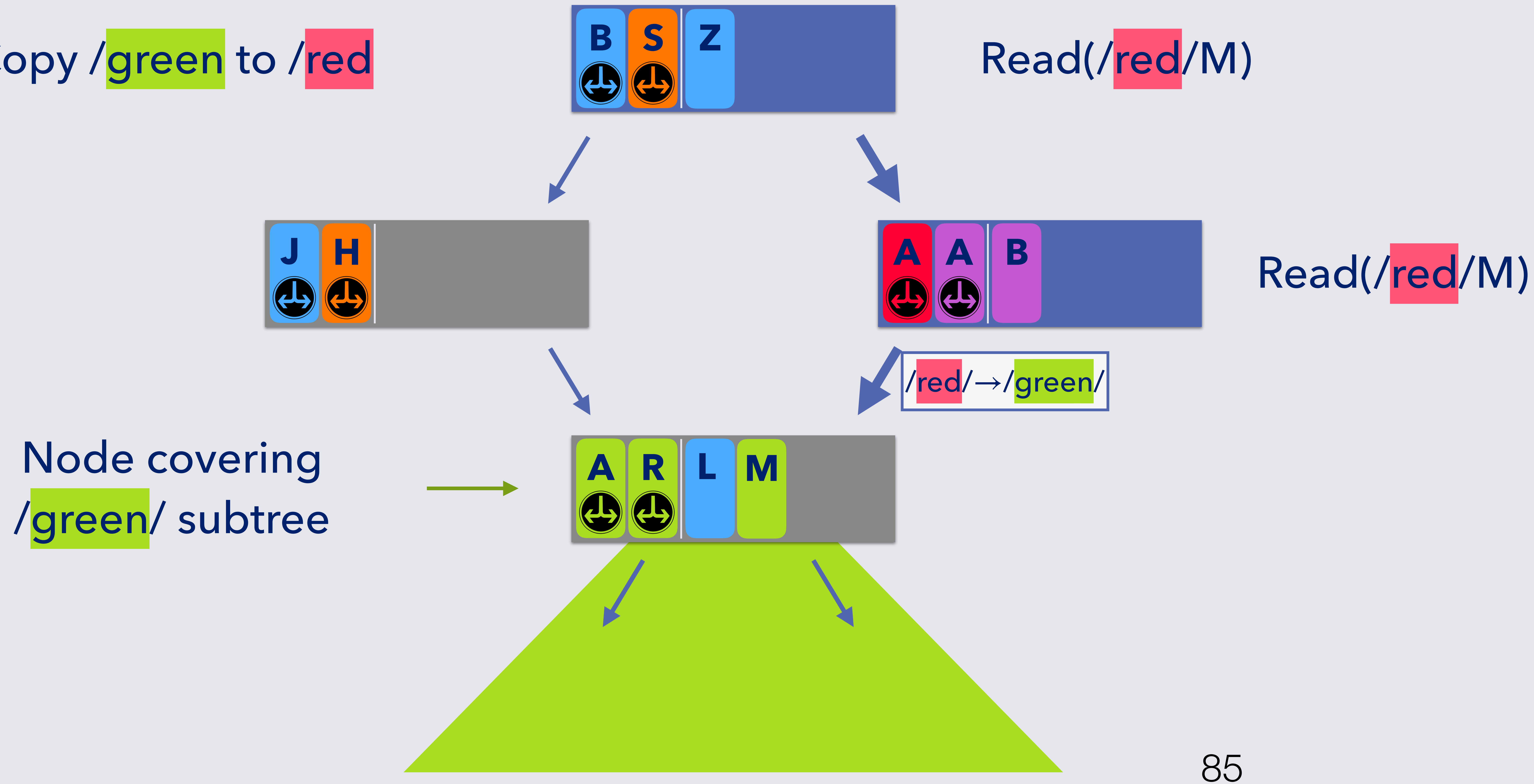
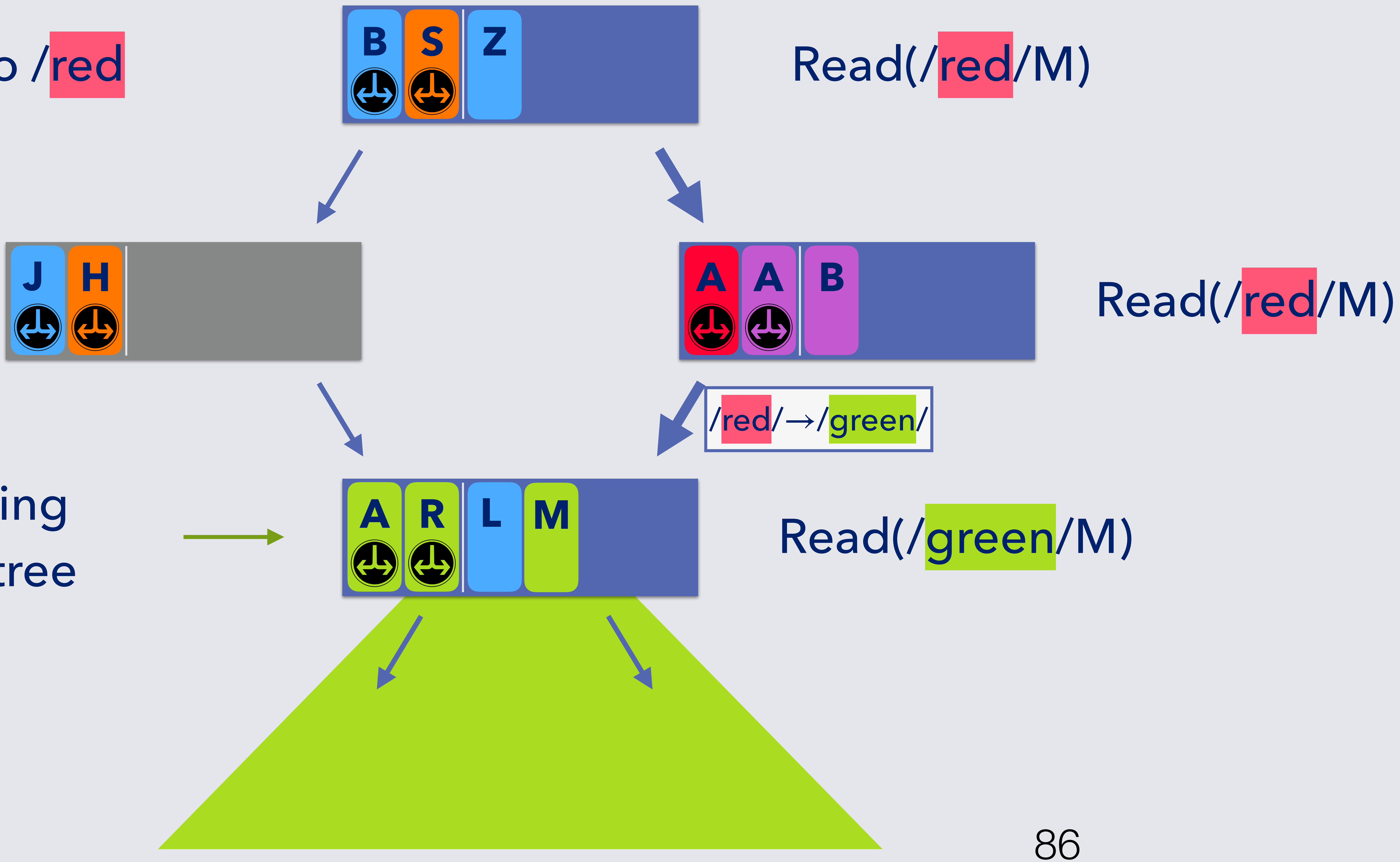


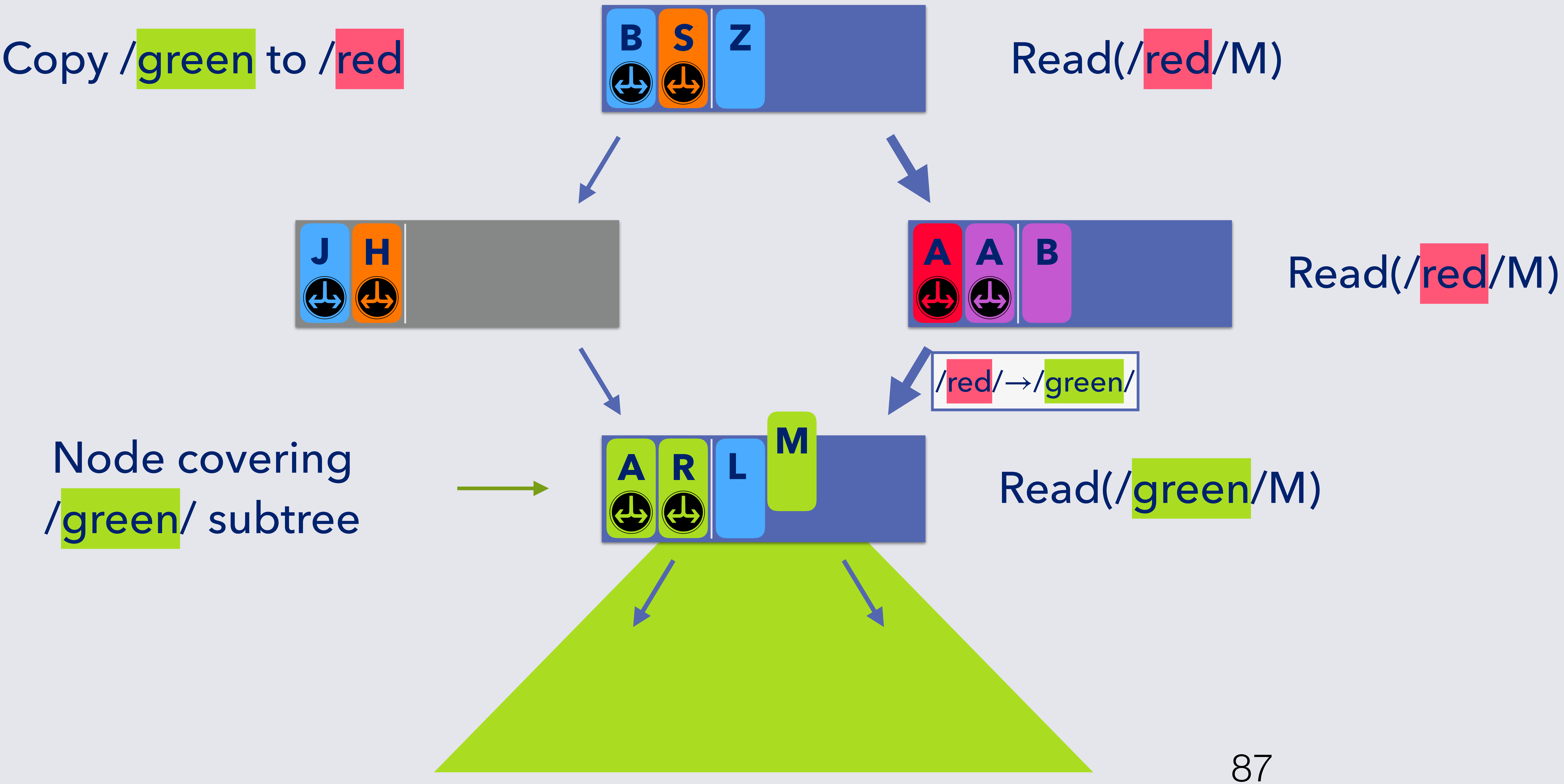
Logical Copy with Bε-DAGs

Copy /green to /red

Node covering /green/ subtree



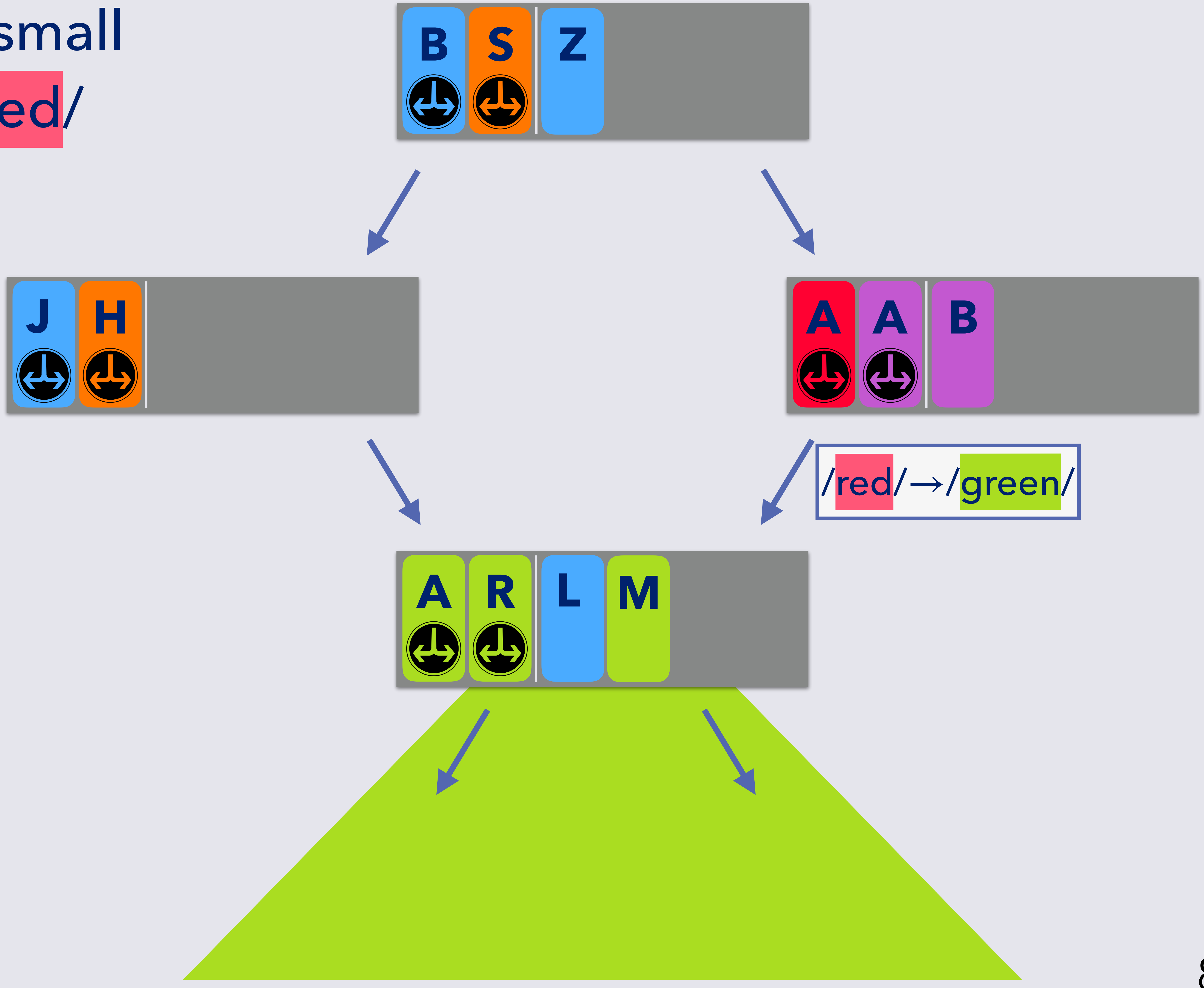
Logical Copy with Bε-DAGs



B^{ε}-DAGs and Small Writes

Bε-DAGs and Small Writes

Make some small writes to /red/



Bε-DAGs and Small Writes

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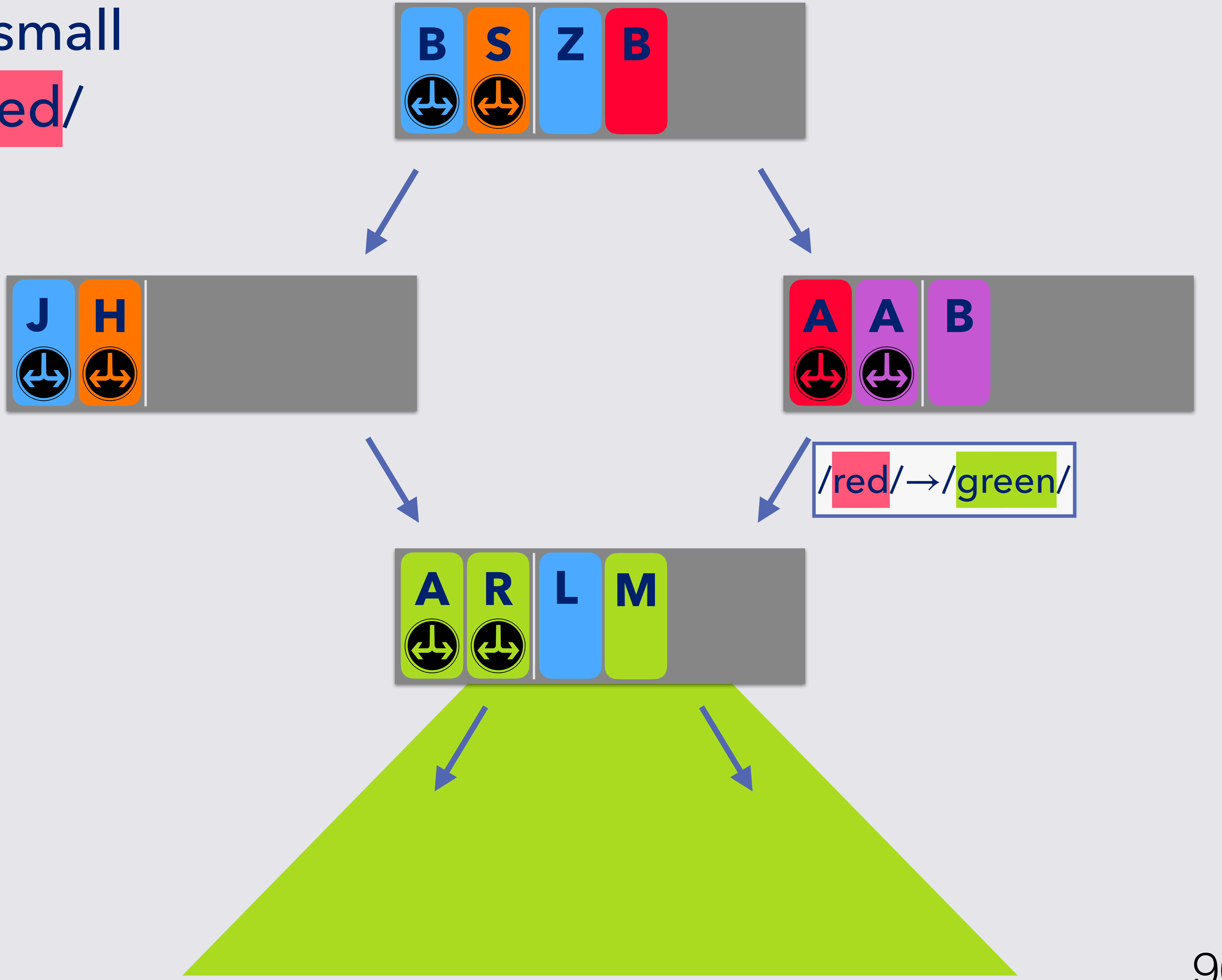

Bε-DAGs and Small Writes

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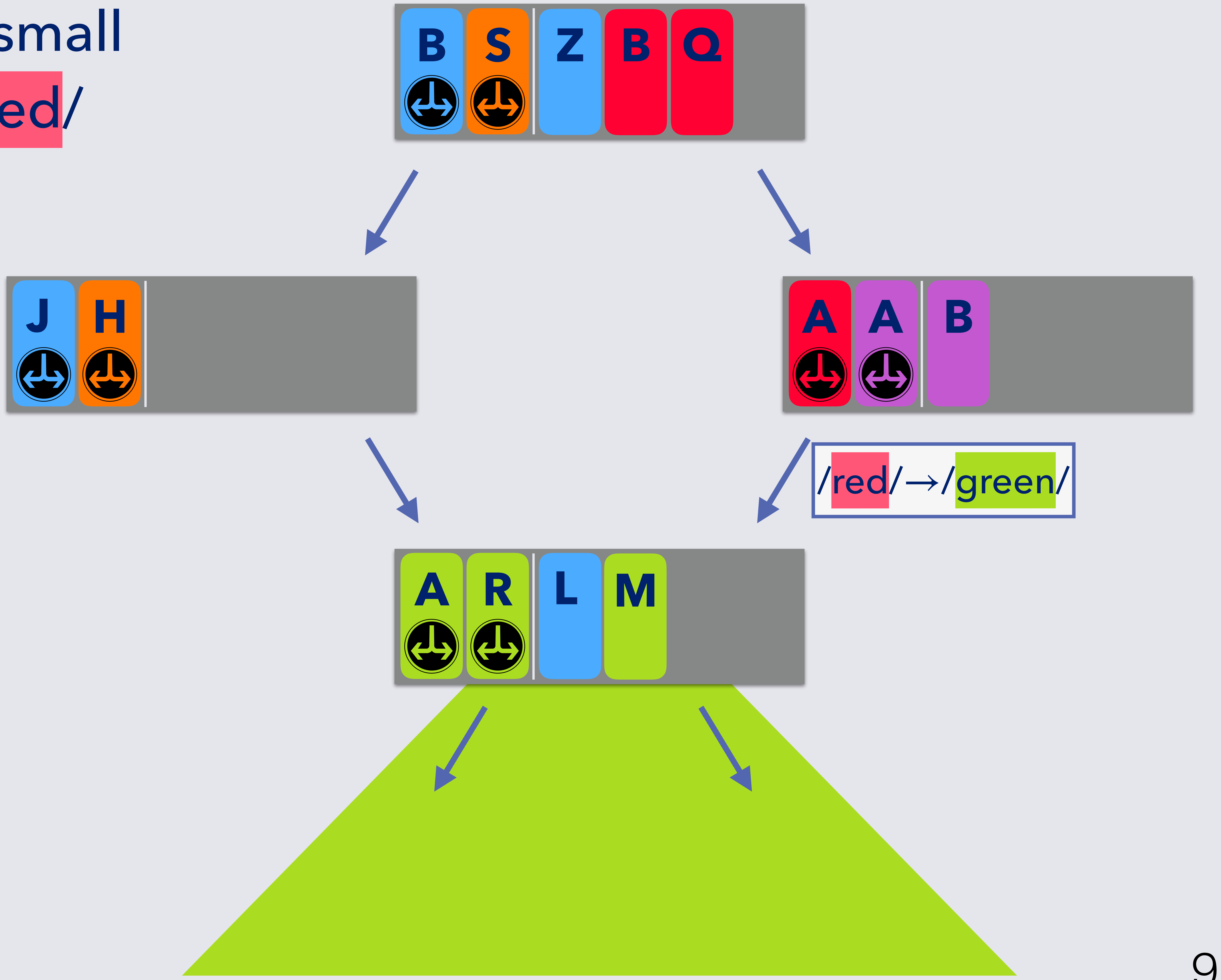

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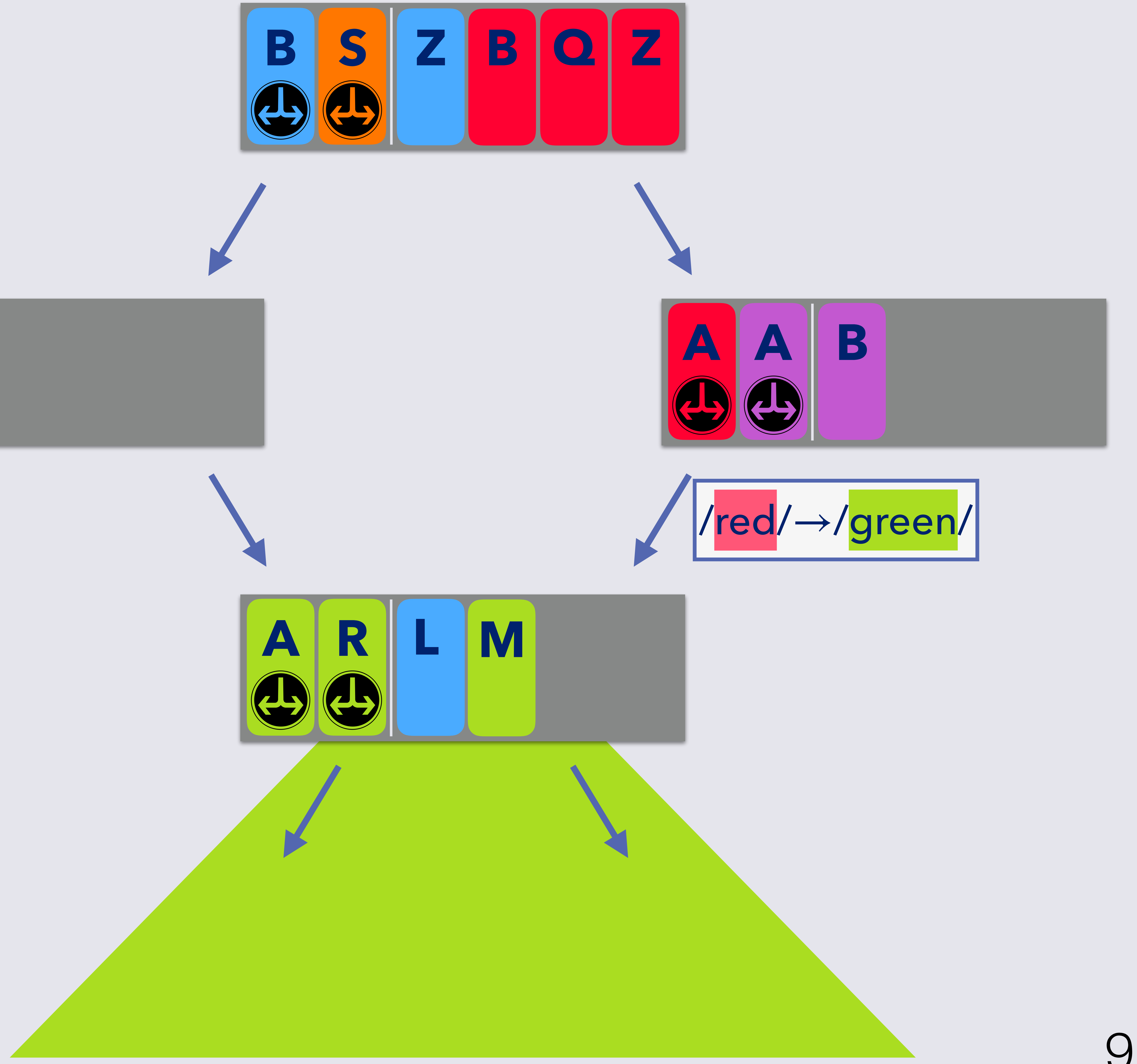

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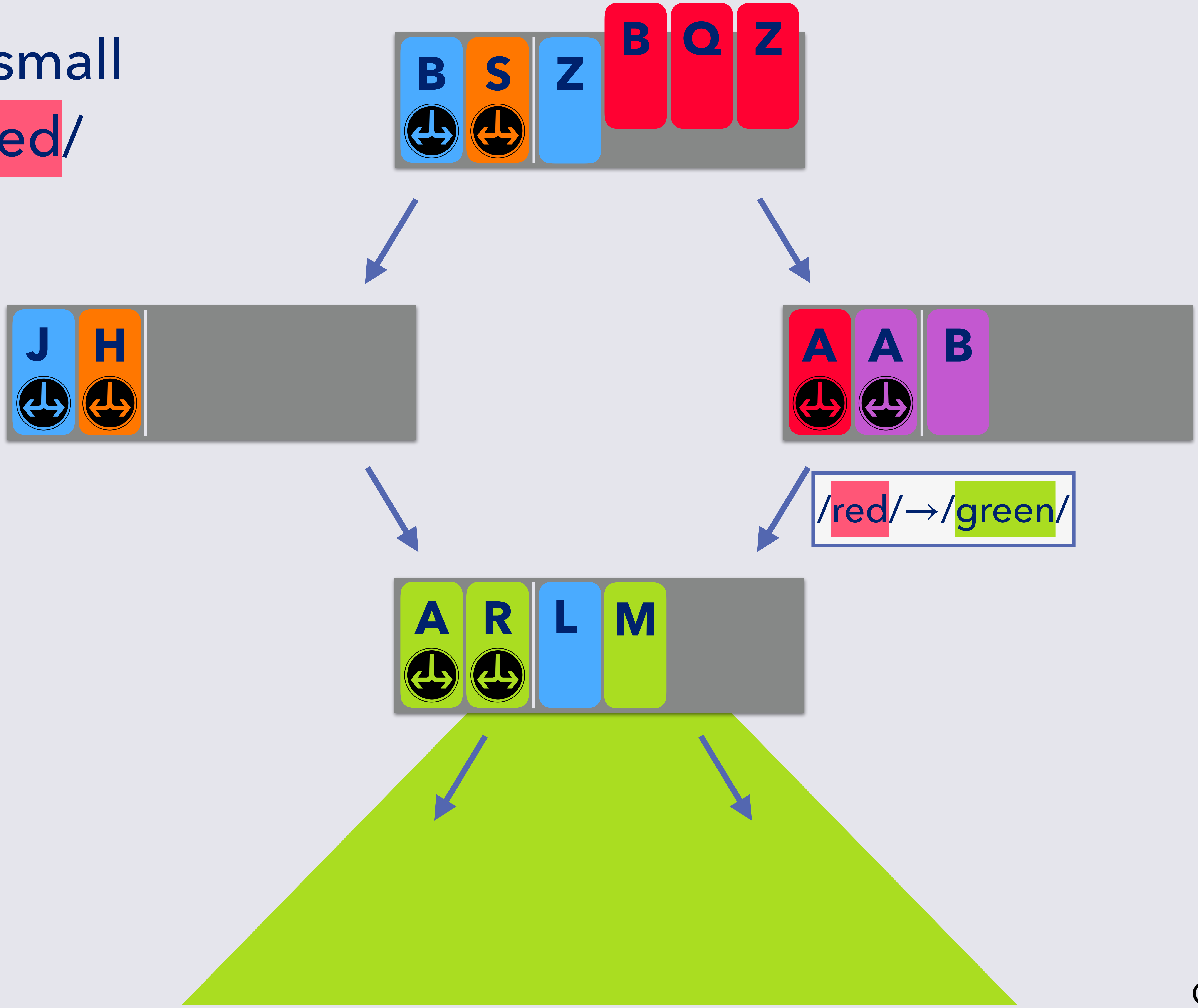
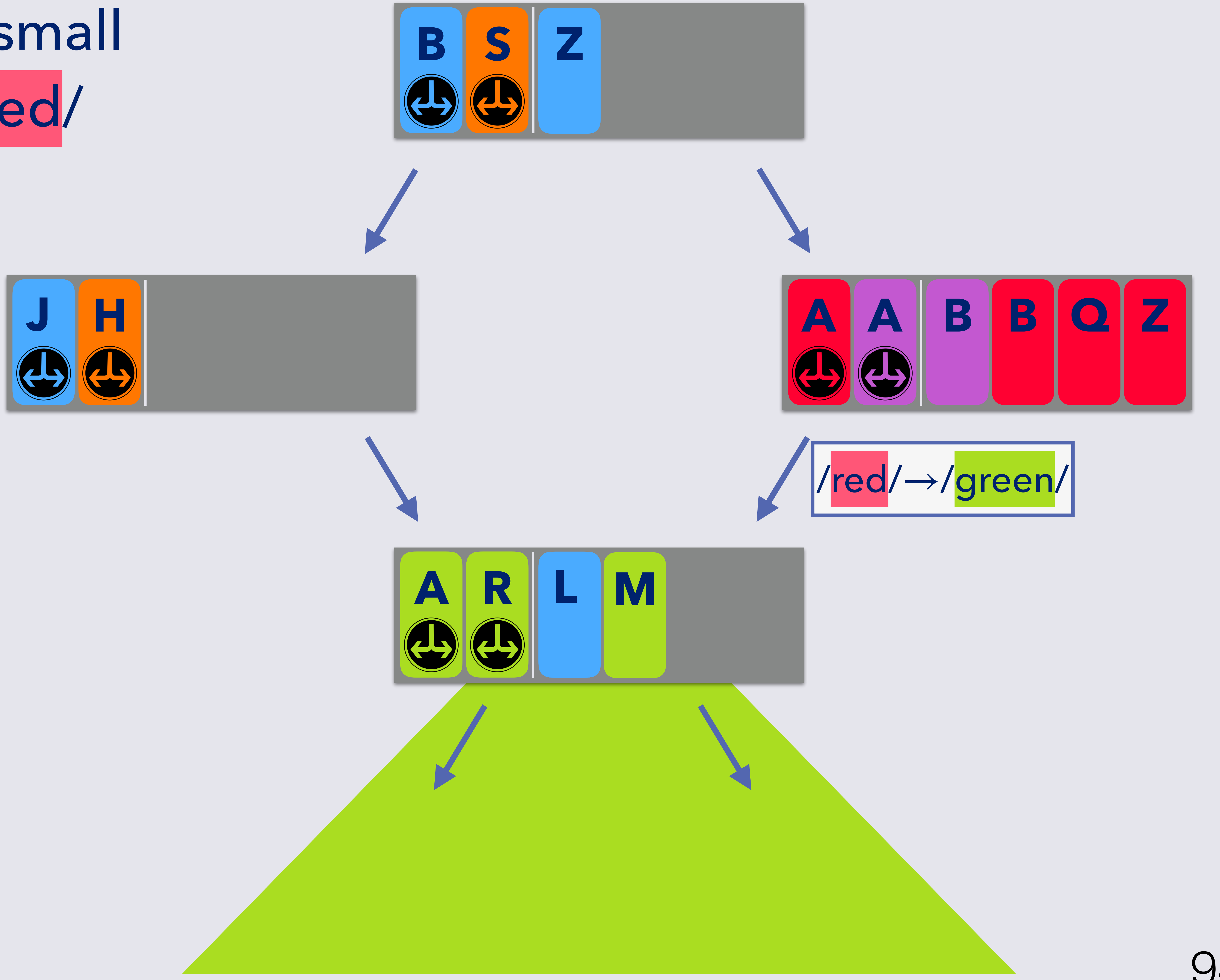


Bε-DAGs and Small Writes

Make some small writes to /red/



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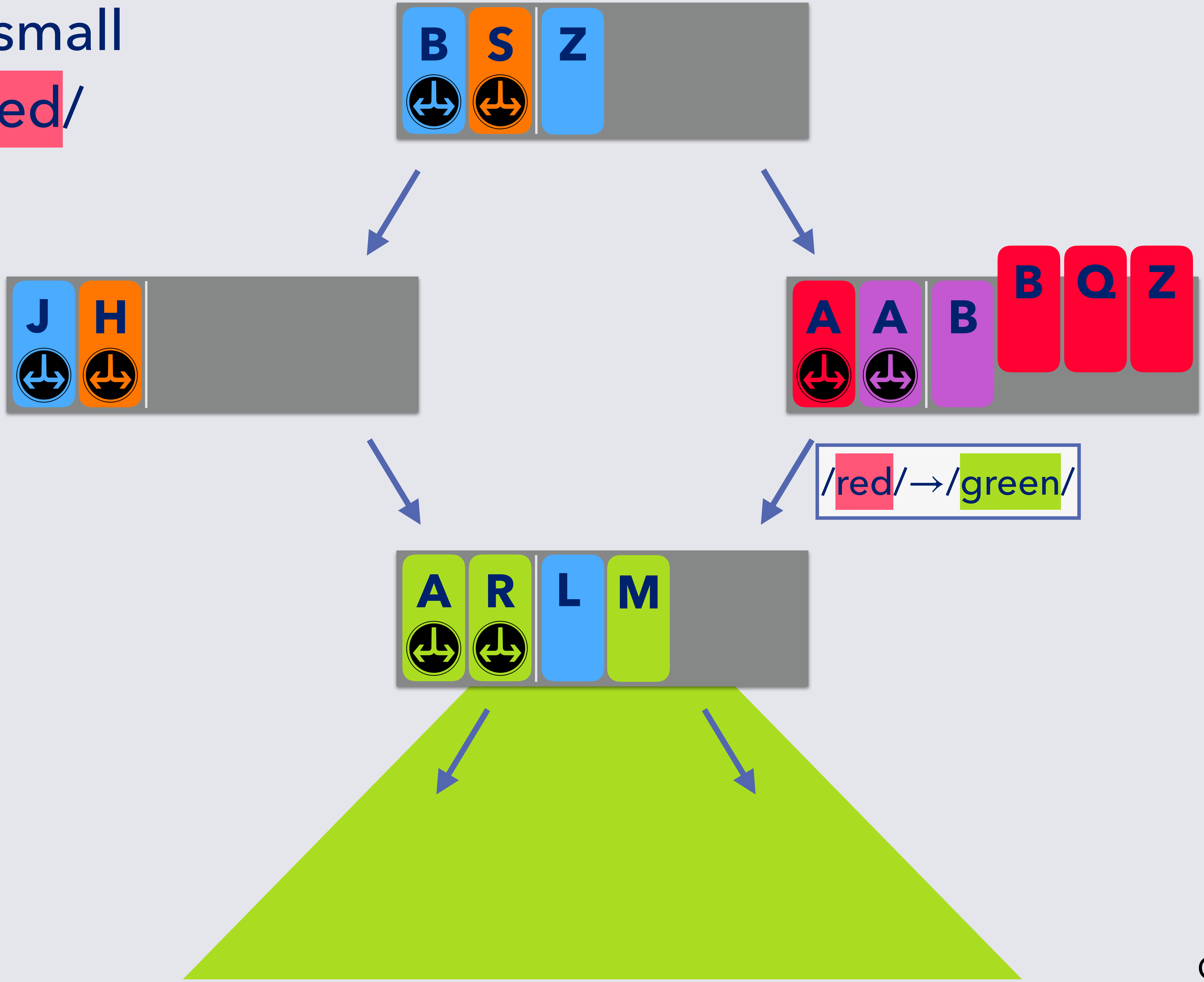
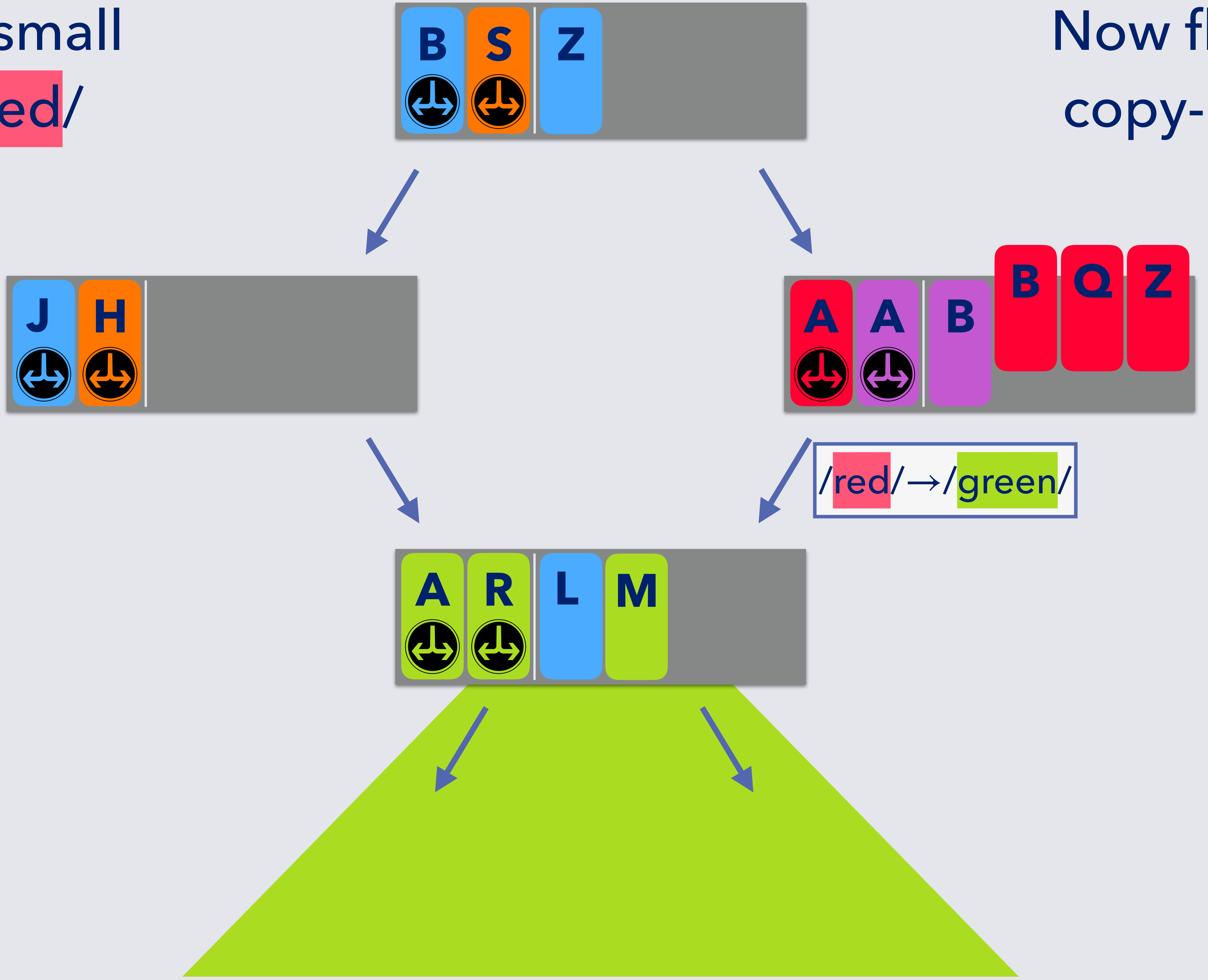
Make some small writes to /red/



Bε-DAGs and Small Writes

Make some small writes to /red/

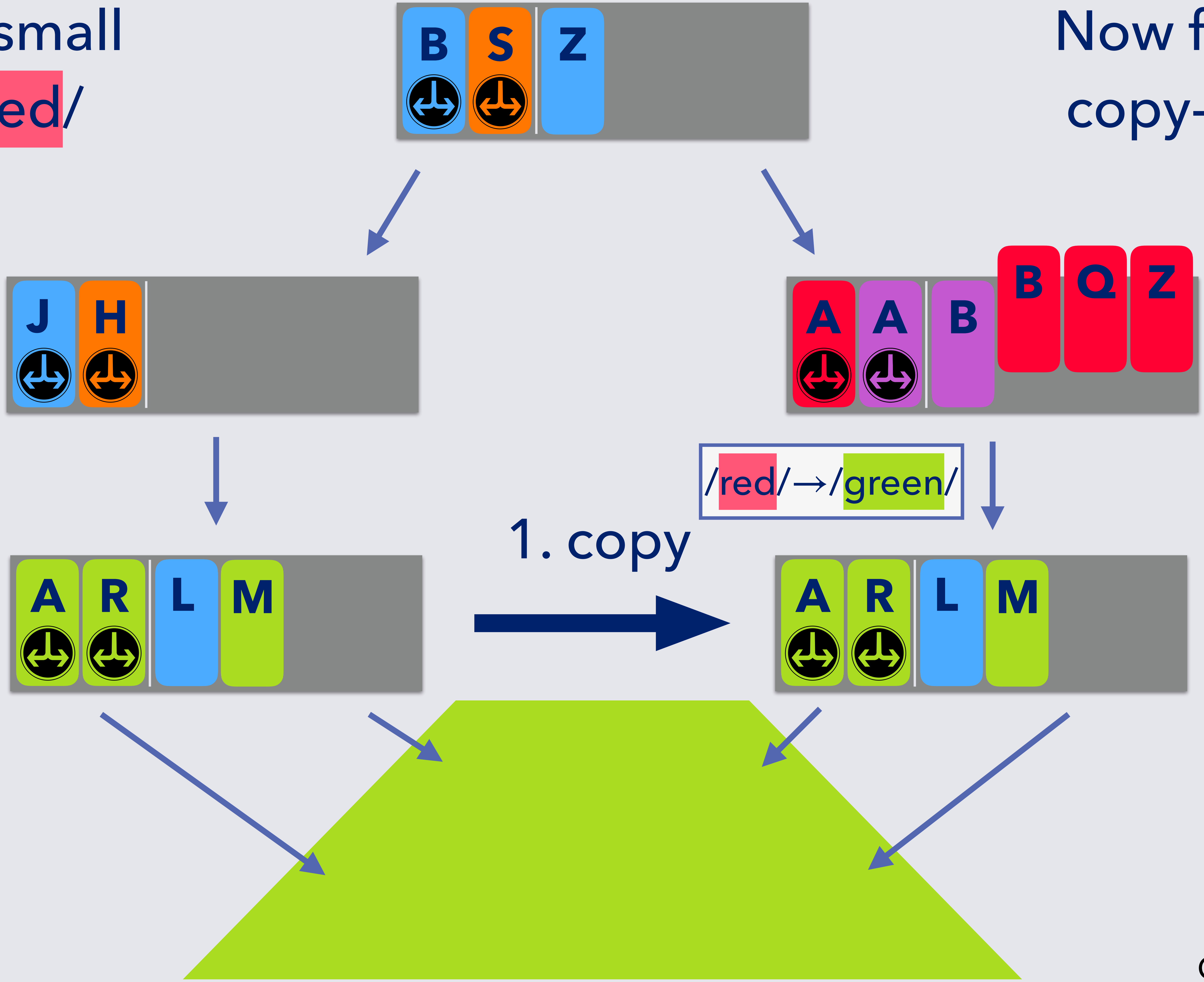
Now flush with copy-on-write



Bε-DAGs and Small Writes

Make some small writes to /red/

Now flush with copy-on-write



Bε-DAGs and Small Writes

Make some small writes to /red/

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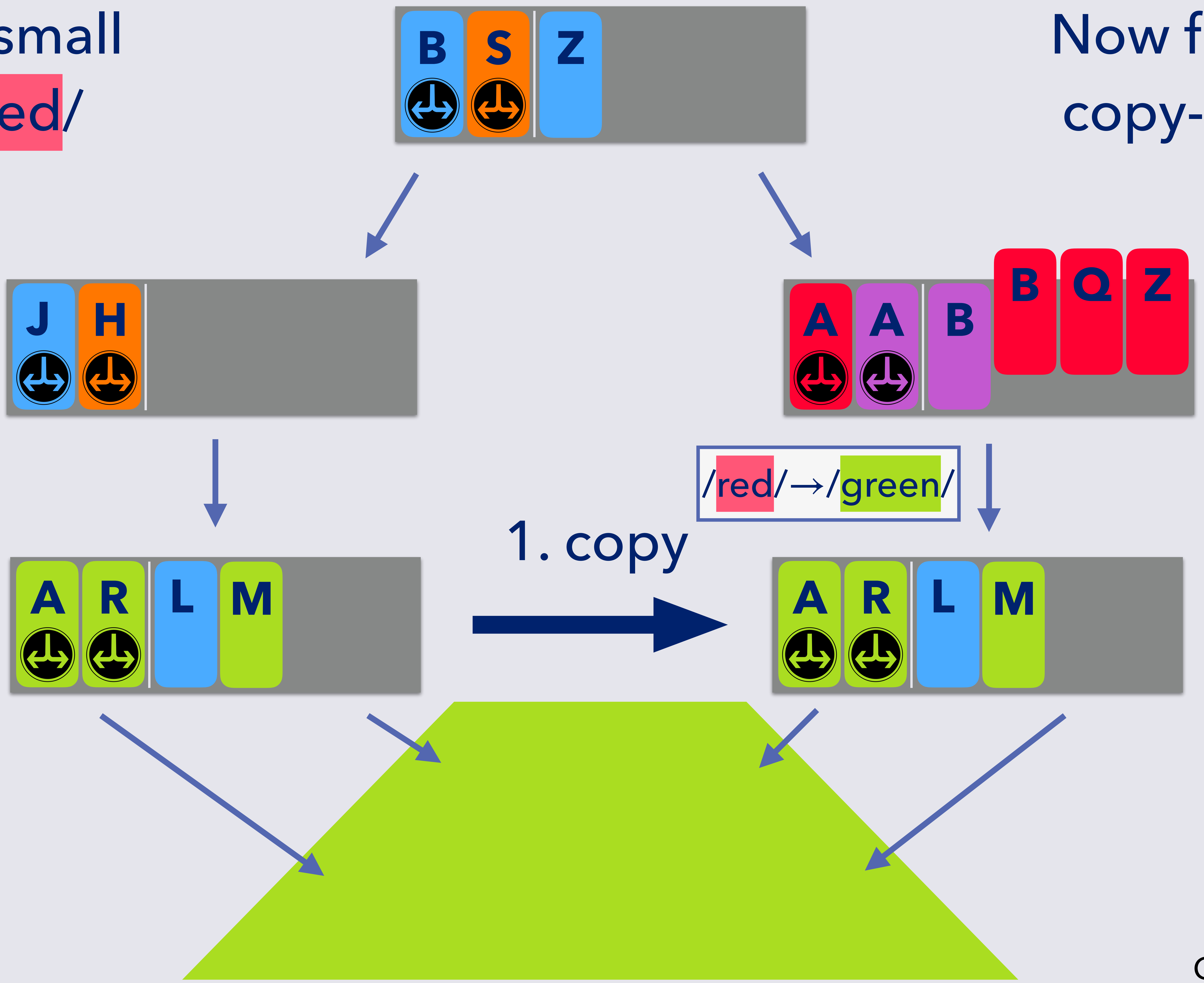
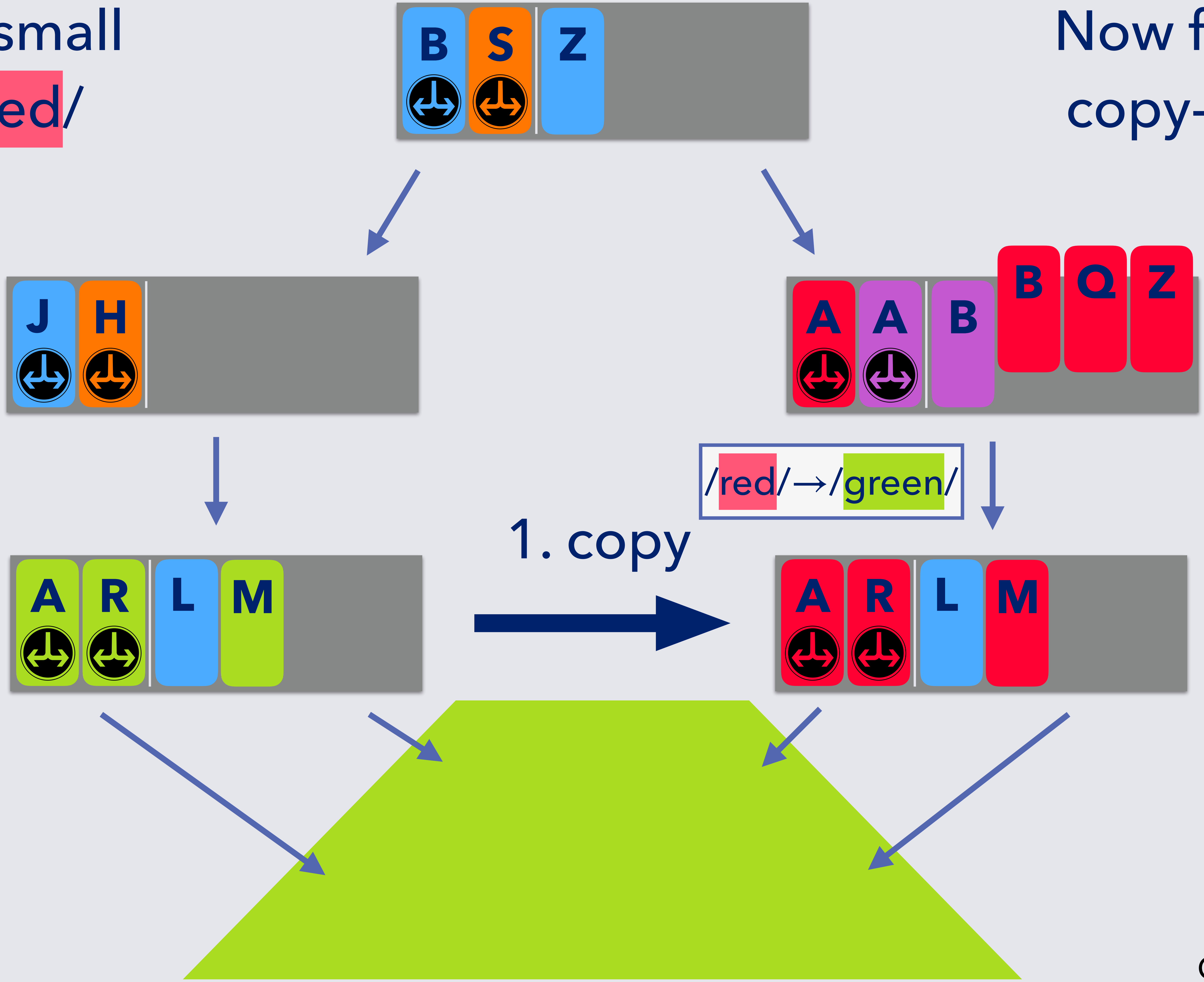


2. Translate /green/→ /red/

Bε-DAGs and Small Writes

Make some small writes to /red/

Now flush with copy-on-write



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Bε-DAGs and Small Writes

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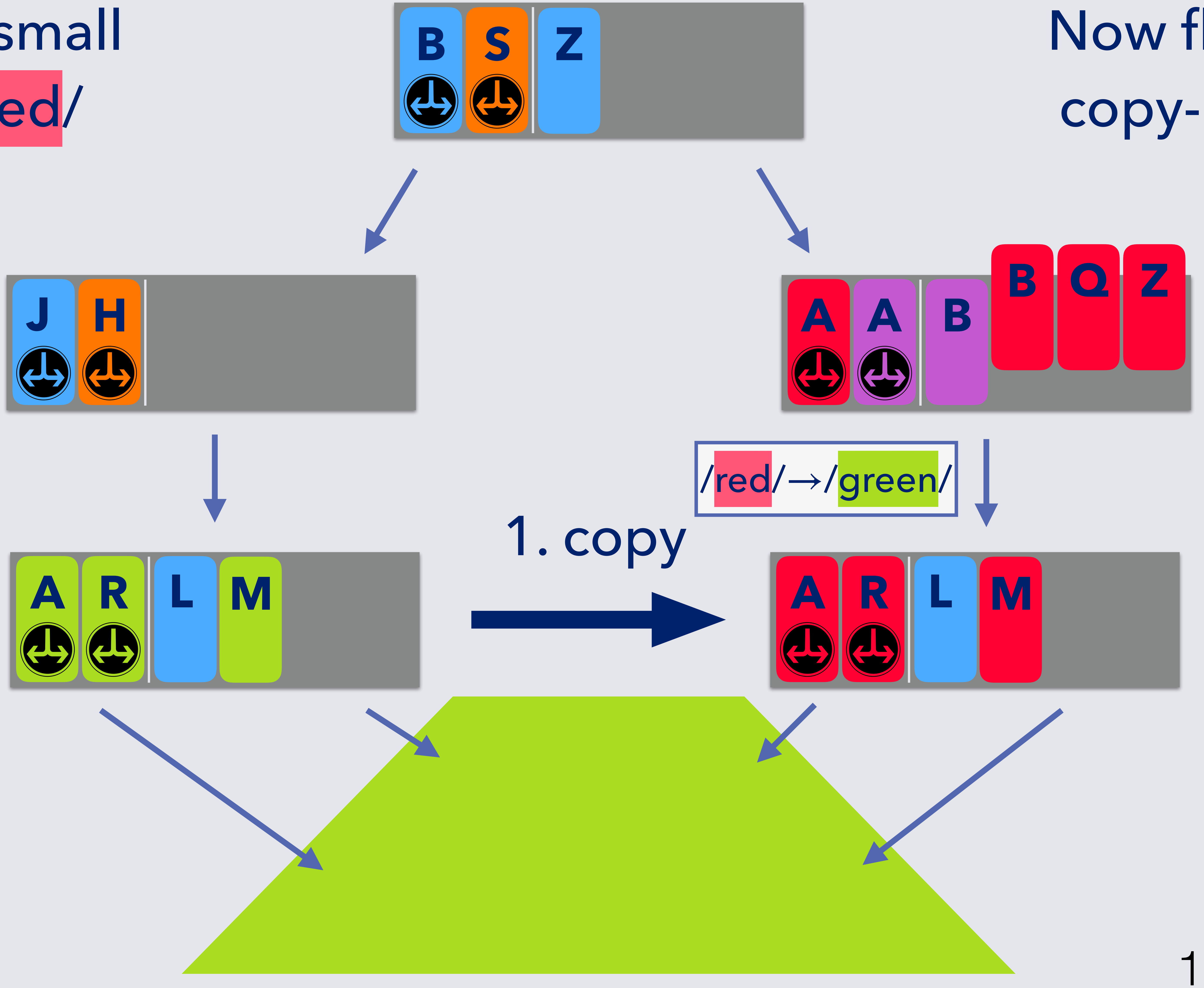
Now flush with copy-on-write



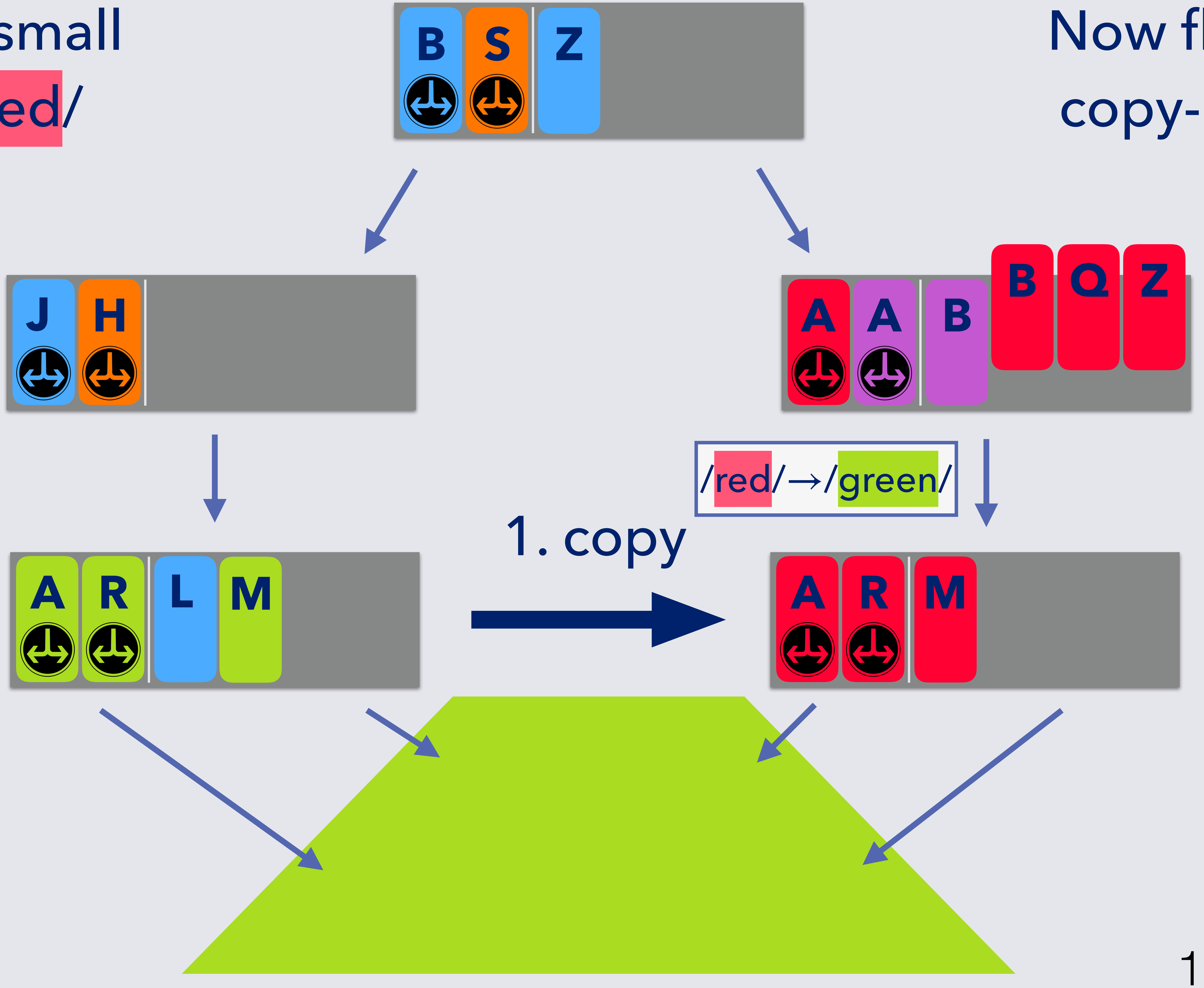
2. Translate /green/→ /red/

3. Delete unreachable data

Bε-DAGs and Small Writes

Make some small writes to /red/

Now flush with copy-on-write



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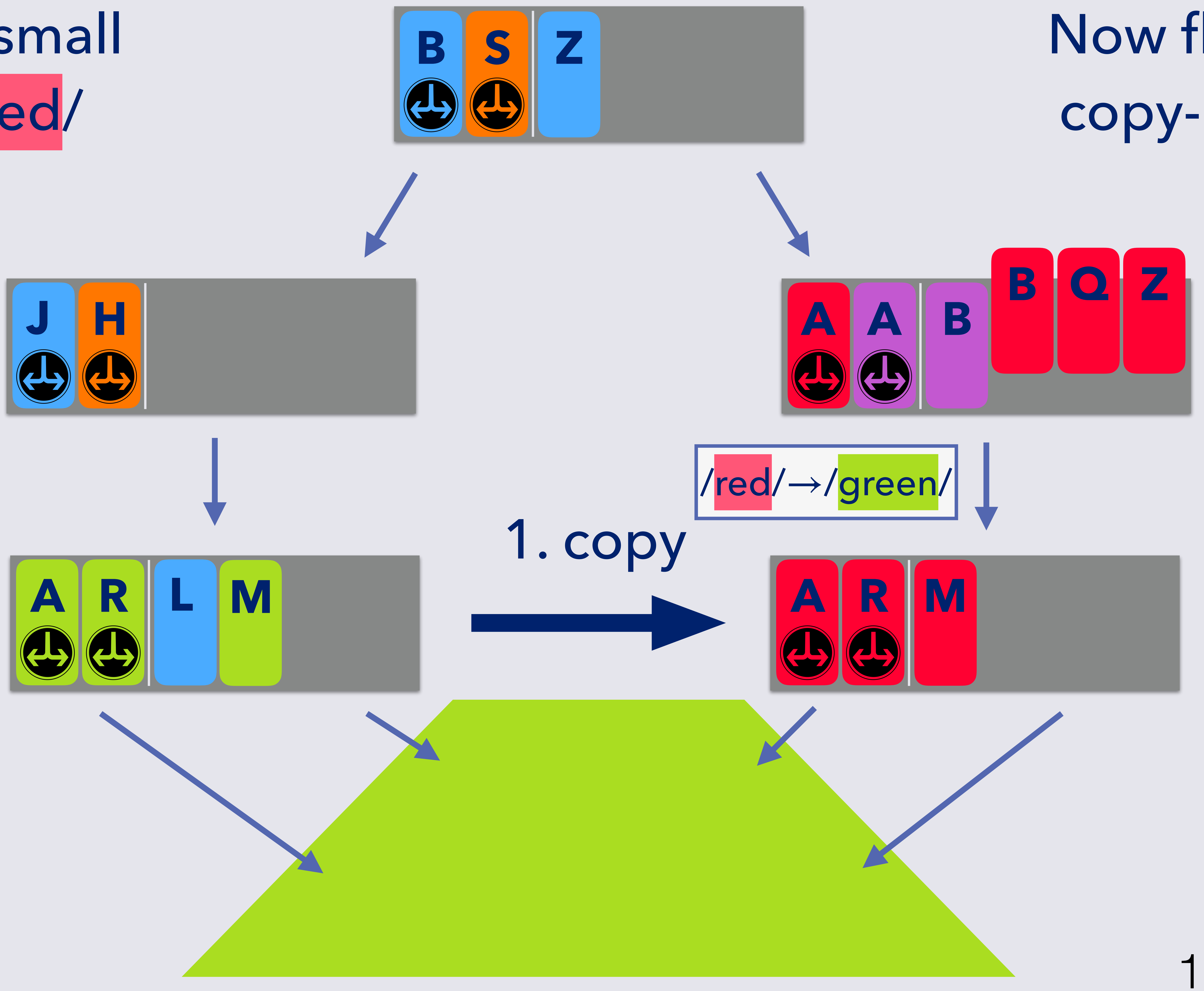
3. Delete unreachable data

Bε-DAGs and Small Writes

Make some small writes to /red/

Now flush with copy-on-write



2. Translate /green/→ /red/

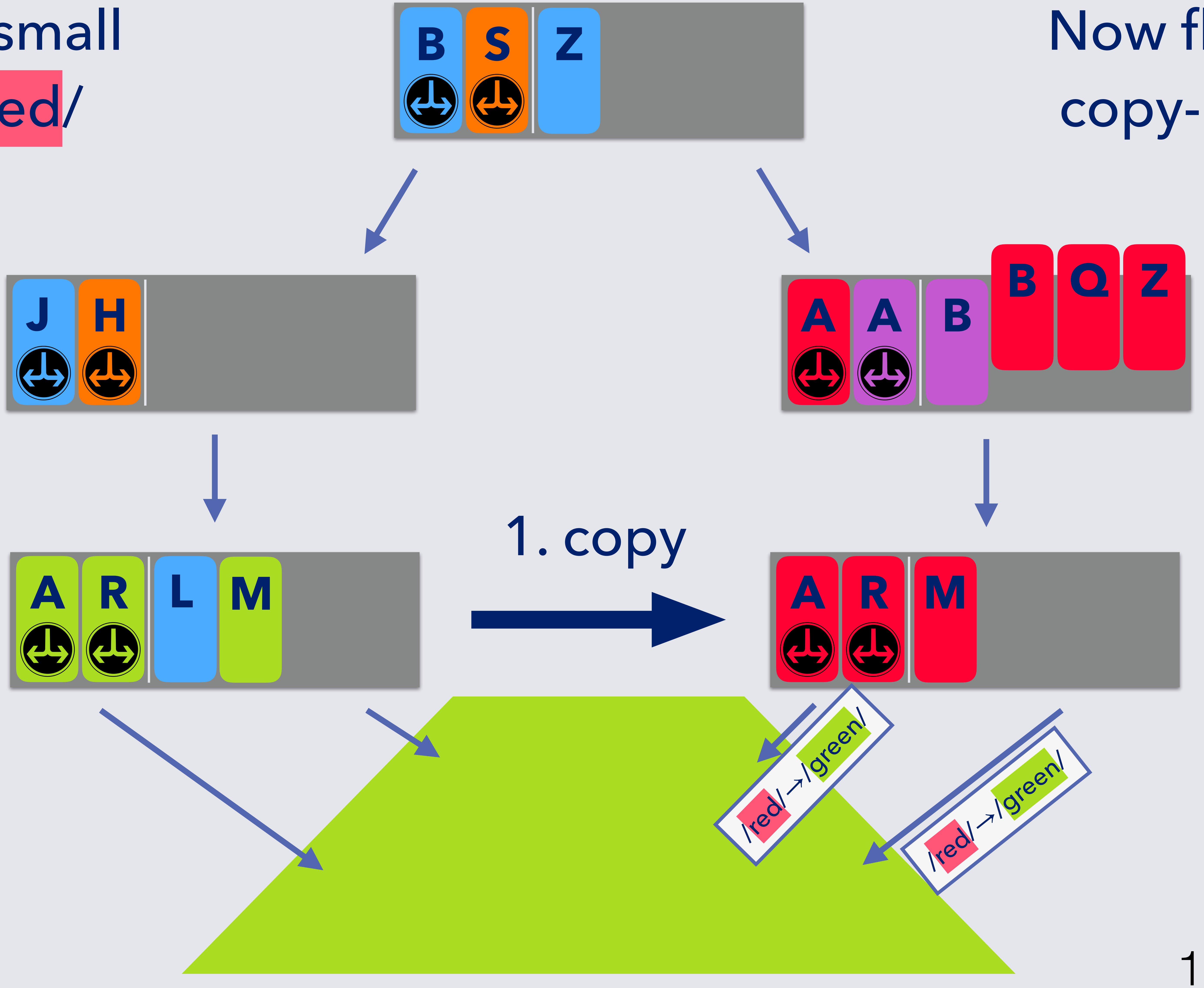
3. Delete unreachable data

4. Move pivot translation

Bε-DAGs and Small Writes

Make some small writes to /red/

Now flush with copy-on-write



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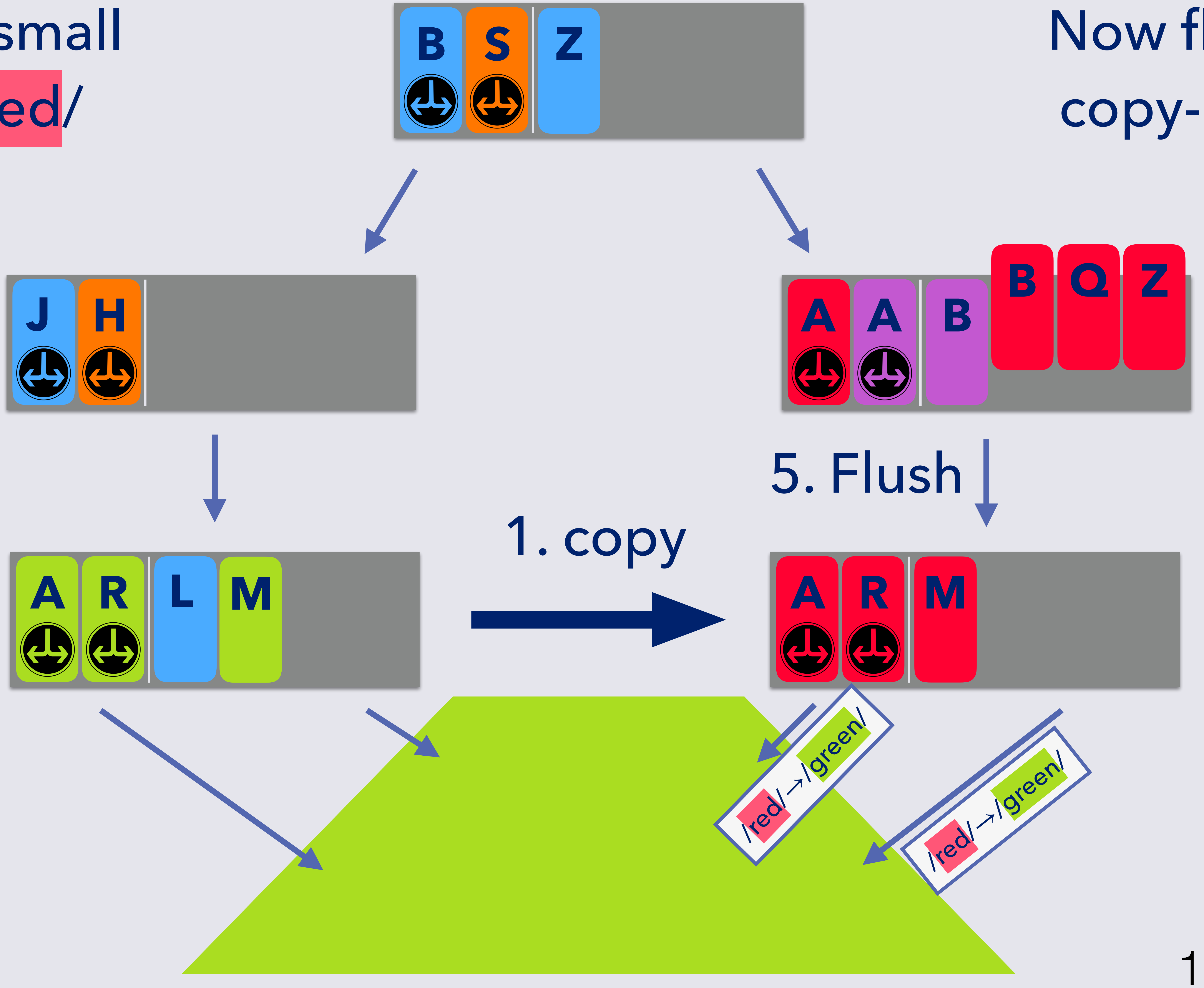
3. Delete unreachable data

4. Move pivot translation

Bε-DAGs and Small Writes

Make some small writes to /red/

Now flush with copy-on-write



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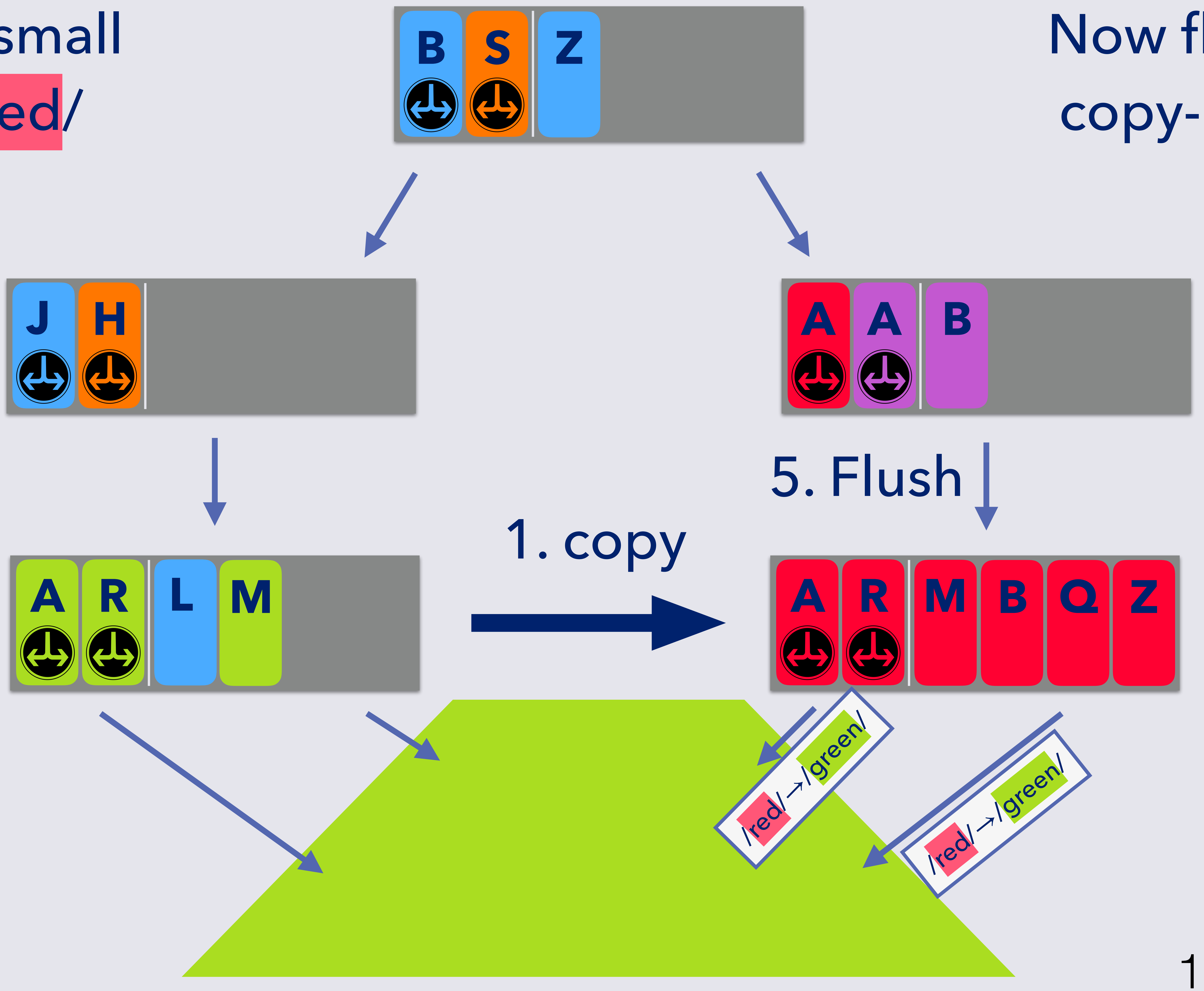
3. Delete unreachable data

4. Move pivot translation

Bε-DAGs and Small Writes

Make some small writes to /red/

Now flush with copy-on-write



2. Translate /green/→ /red/

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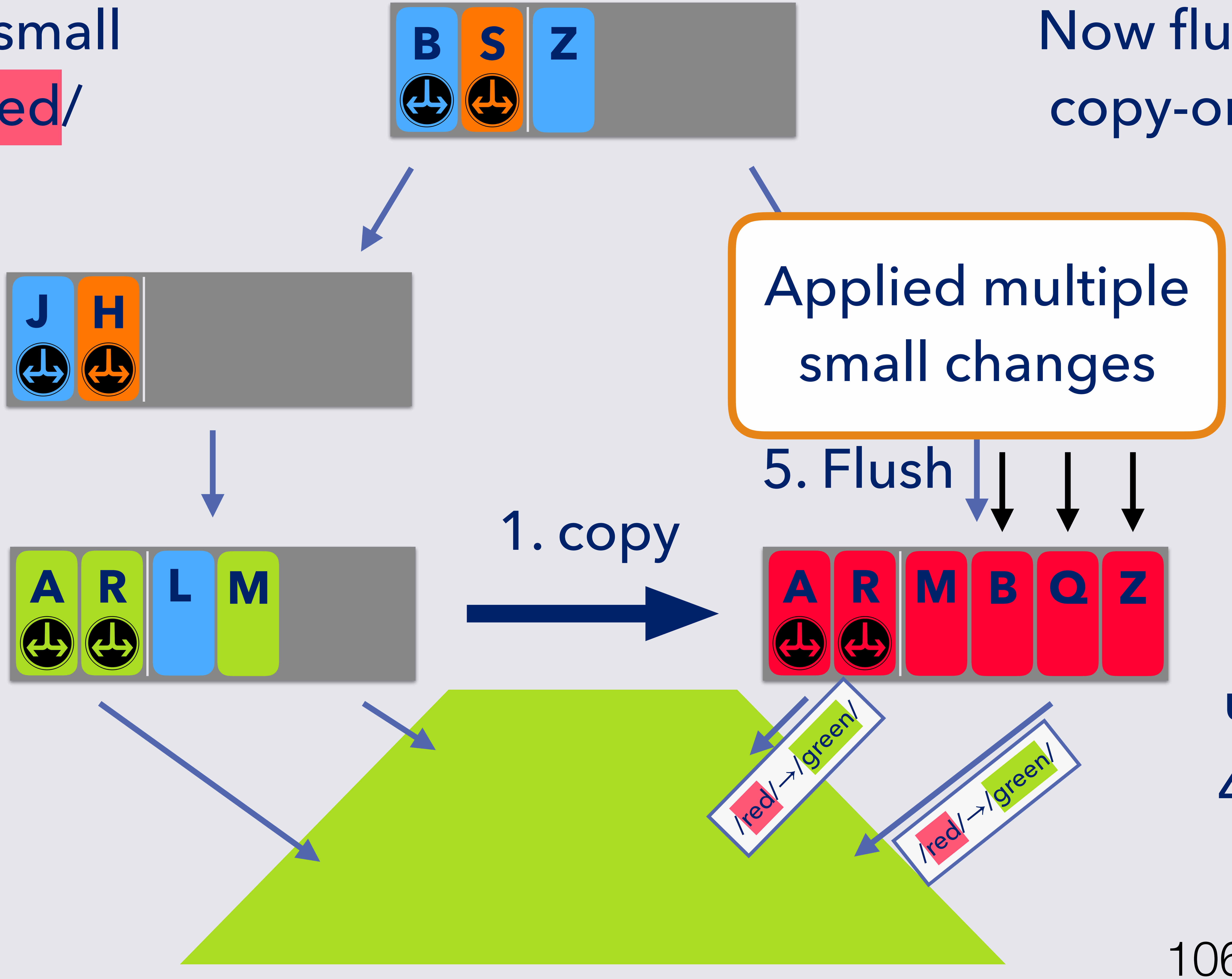
Bε-DAGs and Small Writes

Make some small writes to /red/

Now flush with copy-on-write



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3. Delete unreachable data

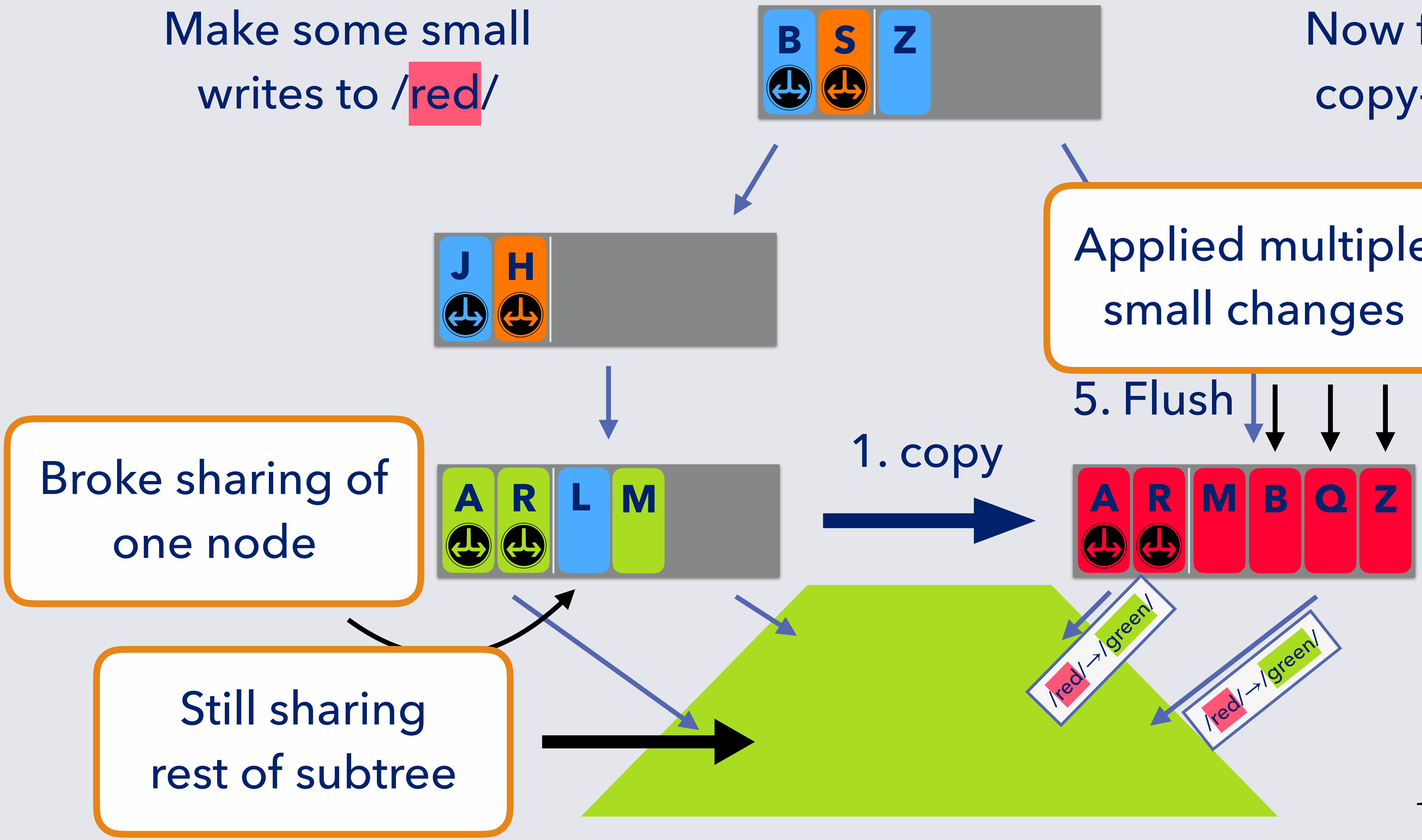
4. Move pivot translation

Bε-DAGs and Small Writes

Bε-DAGs and Small Writes

Make some small writes to /red/

Now flush with copy-on-write



2. Translate /green/→ /red/

3. Delete unreachable data

4. Move pivot translation

Bε-DAGs and Small Writes

Logical Copy with B^{ε}-DAGs

Performance Goals

Space efficient ?

Low latency ?

Copy-specific

Fast writes ?

Fast reads ?

General file system

Logical Copy with Bε-DAGs

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Logical Copy with Bε-DAGs

Performance Goals

Copy-on-Abundant-Write

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Reducing Copy Latency in B^{ε}-DAGs

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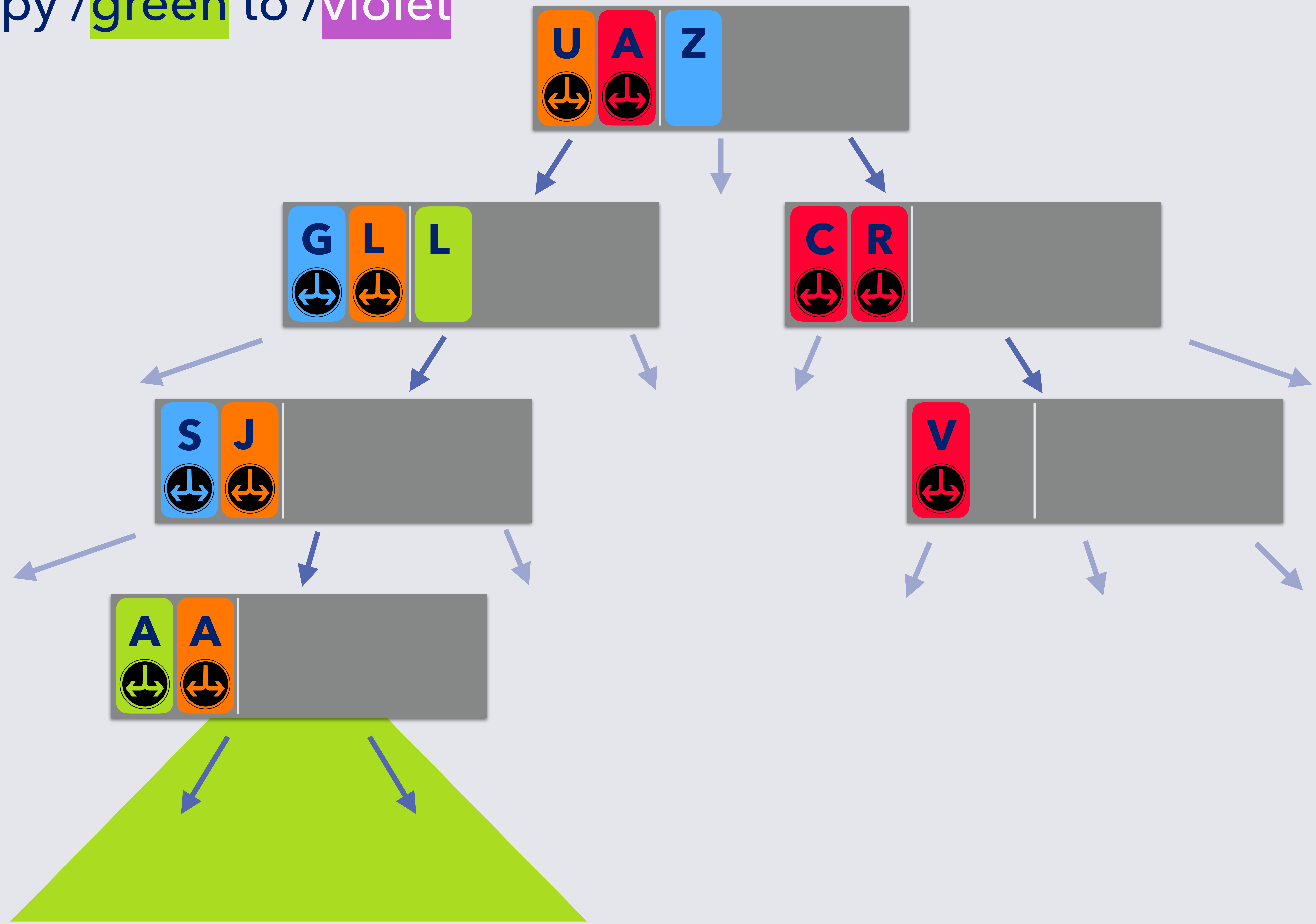

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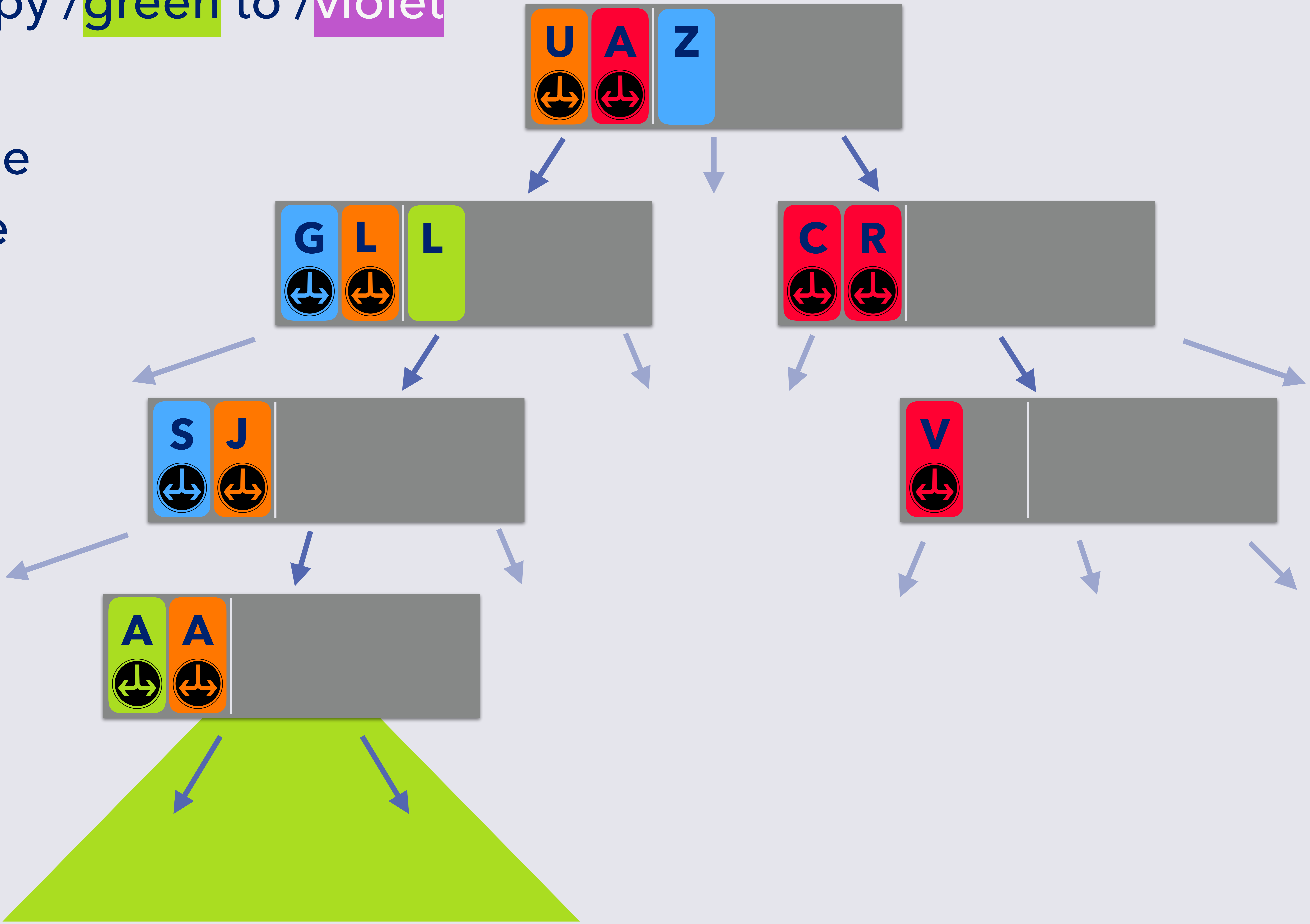

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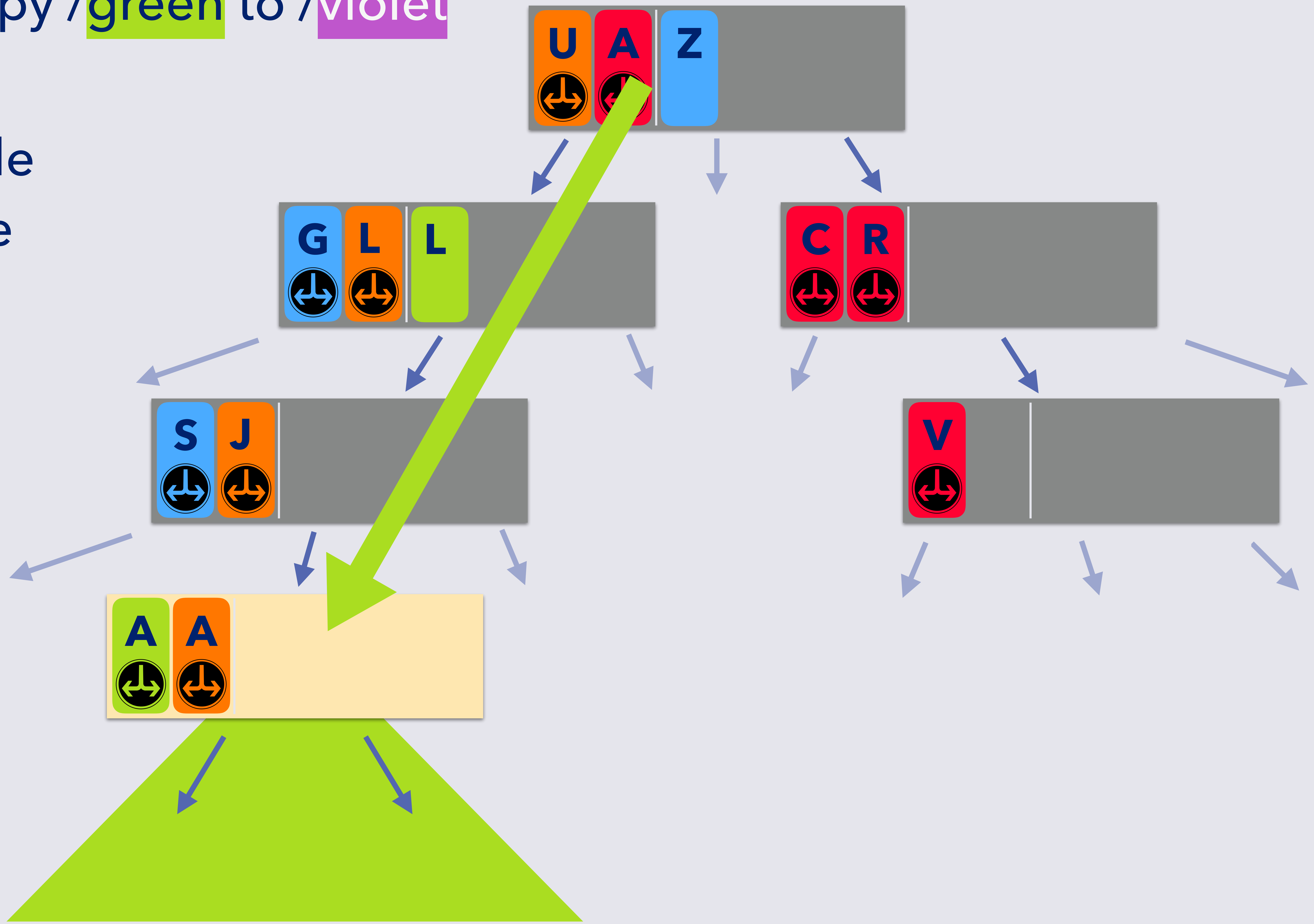

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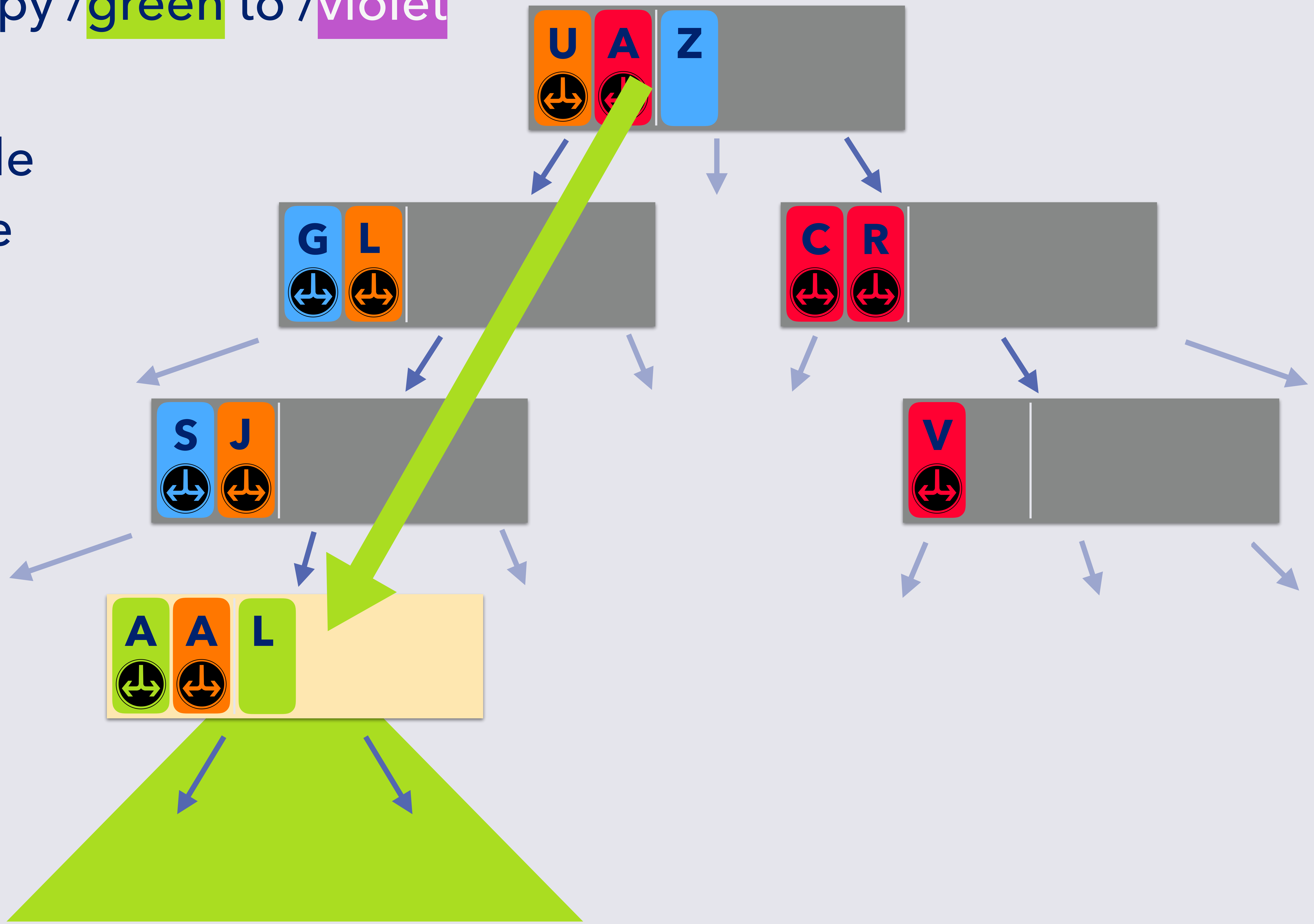

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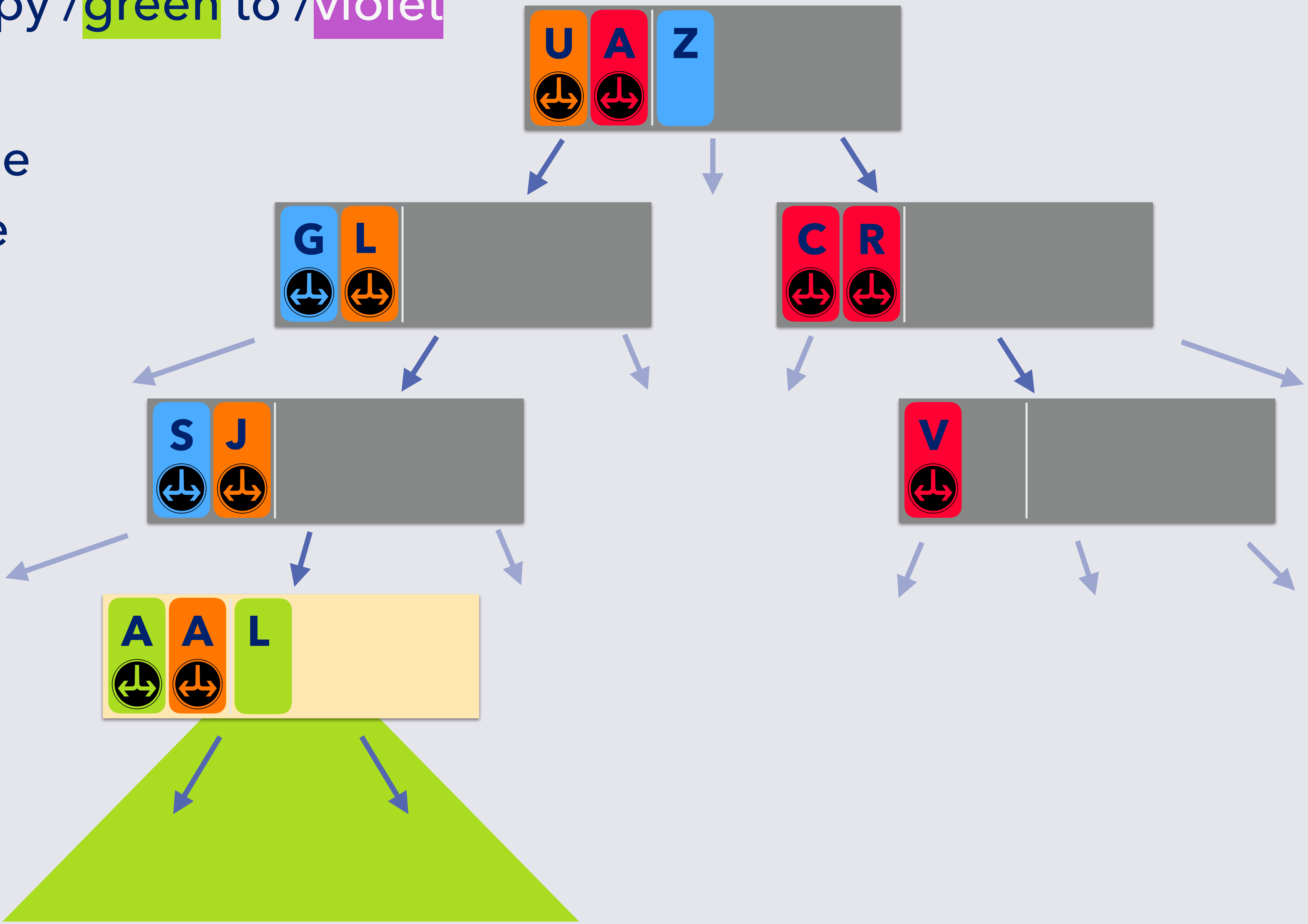

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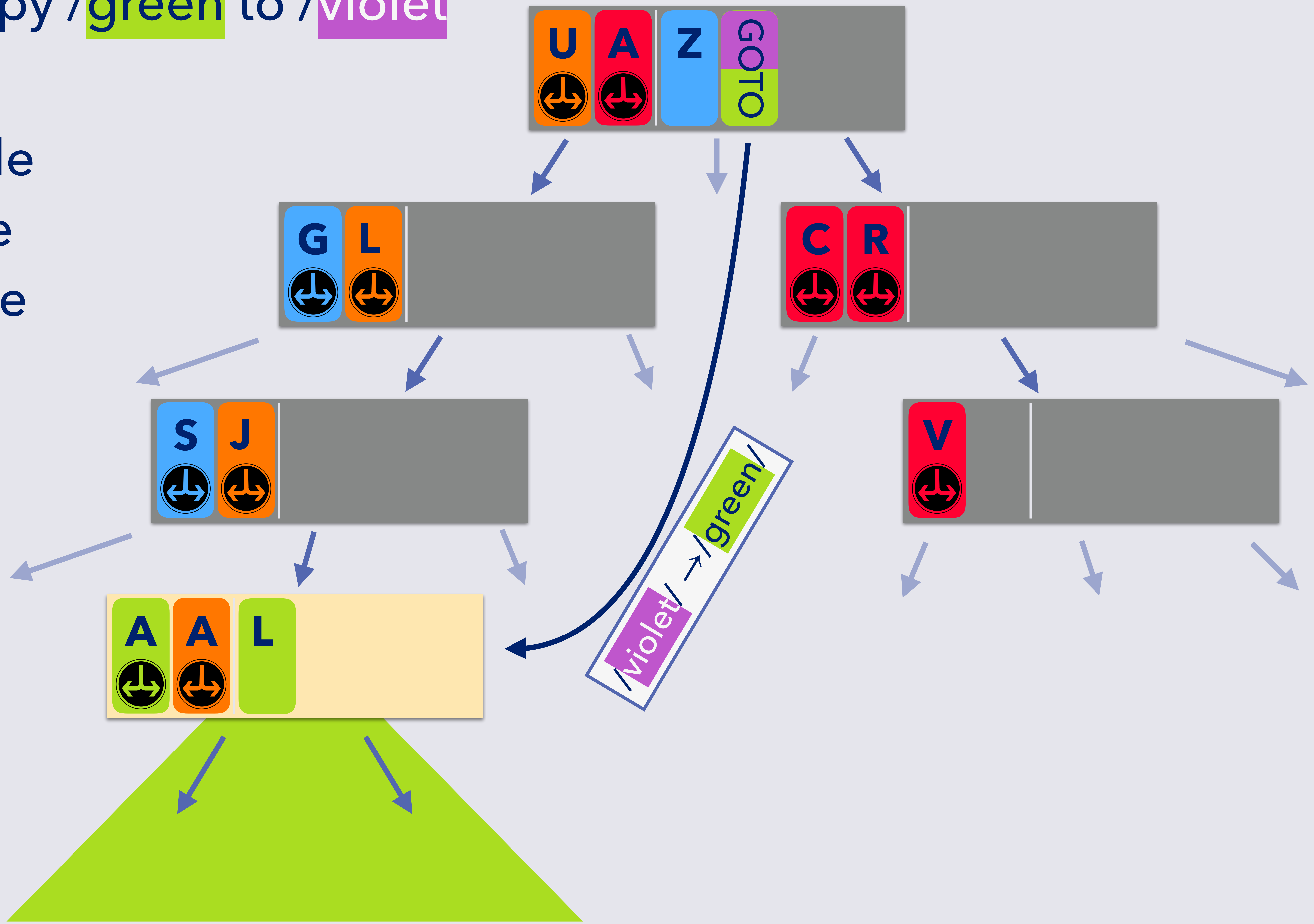

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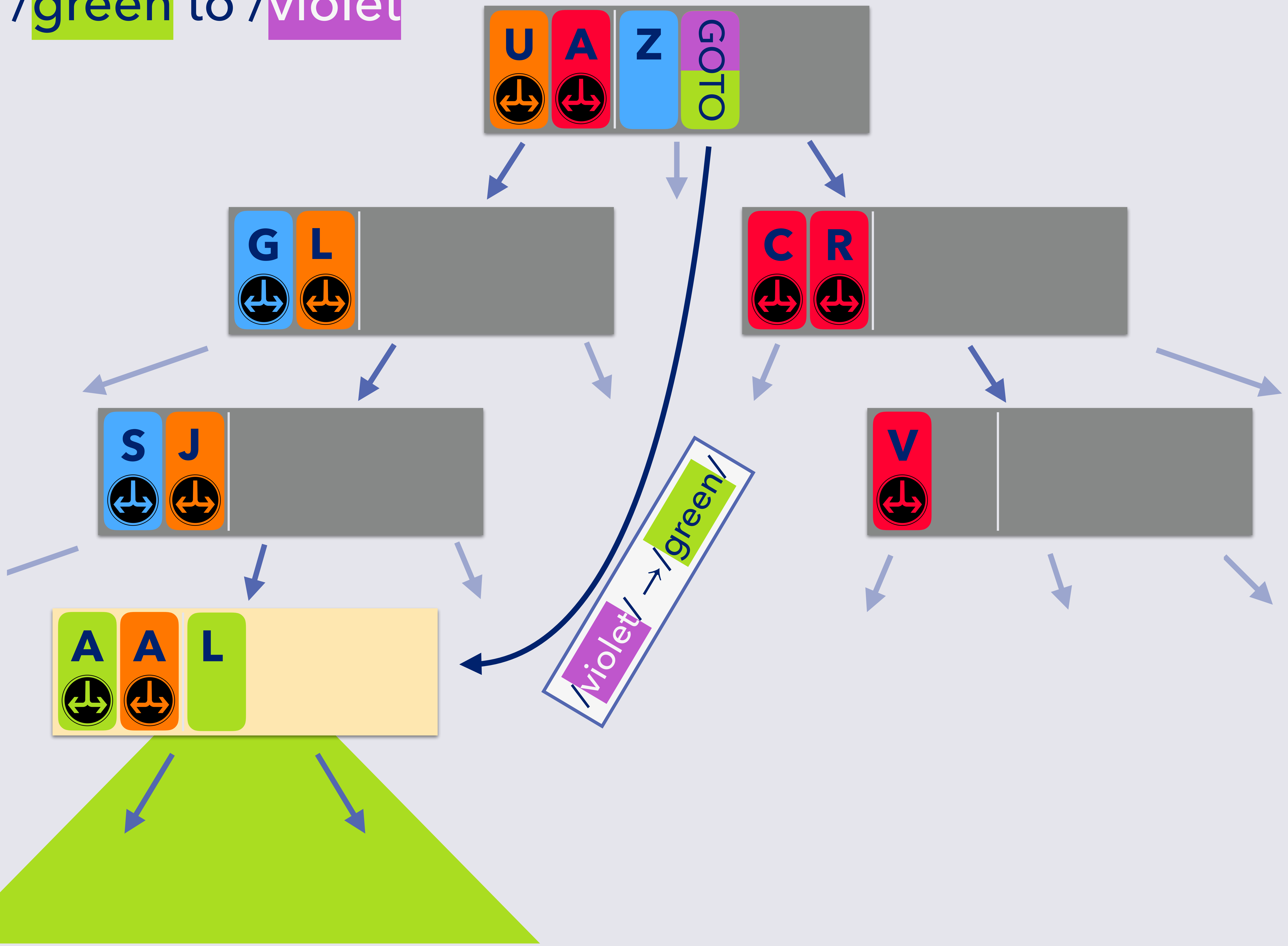

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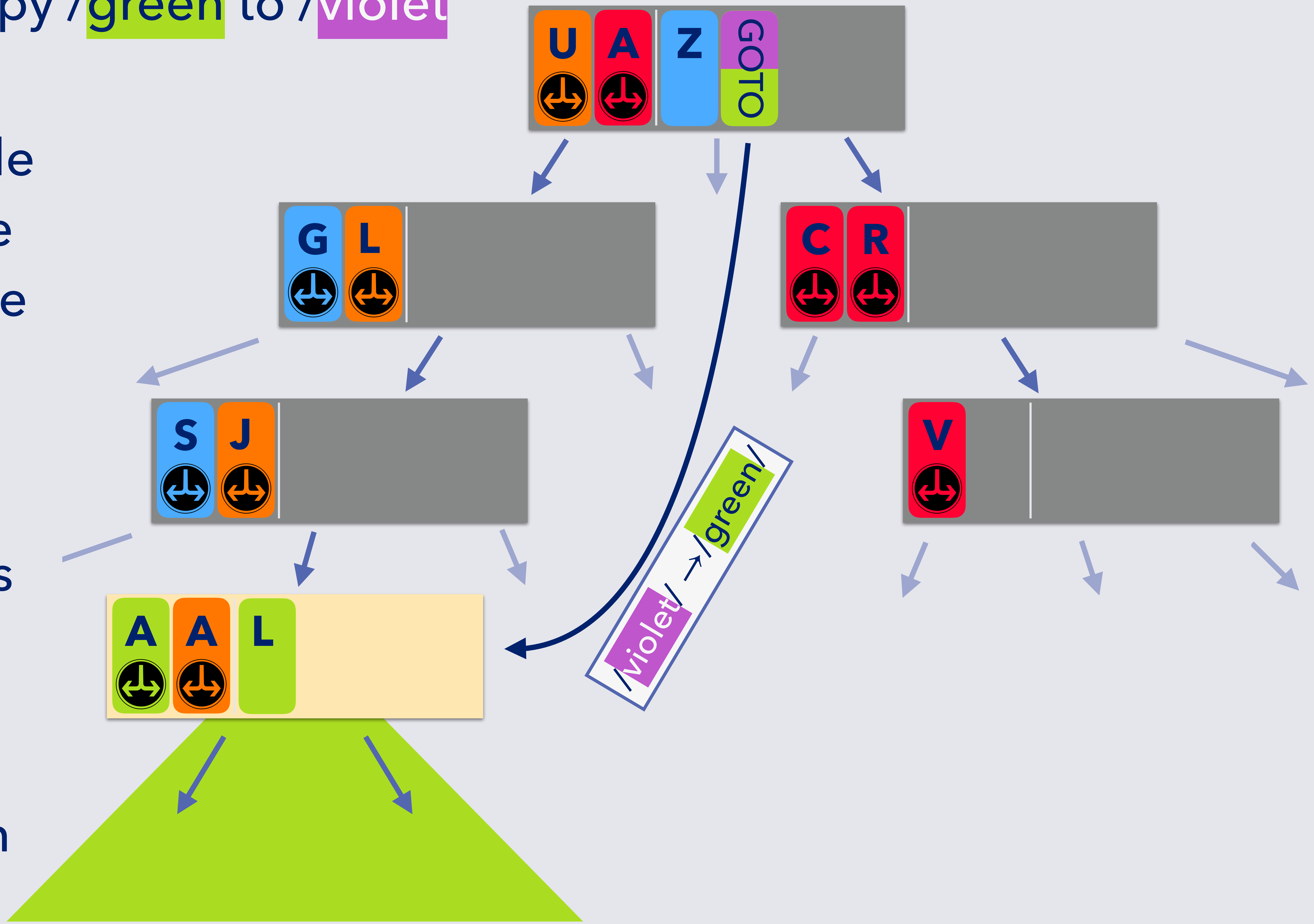

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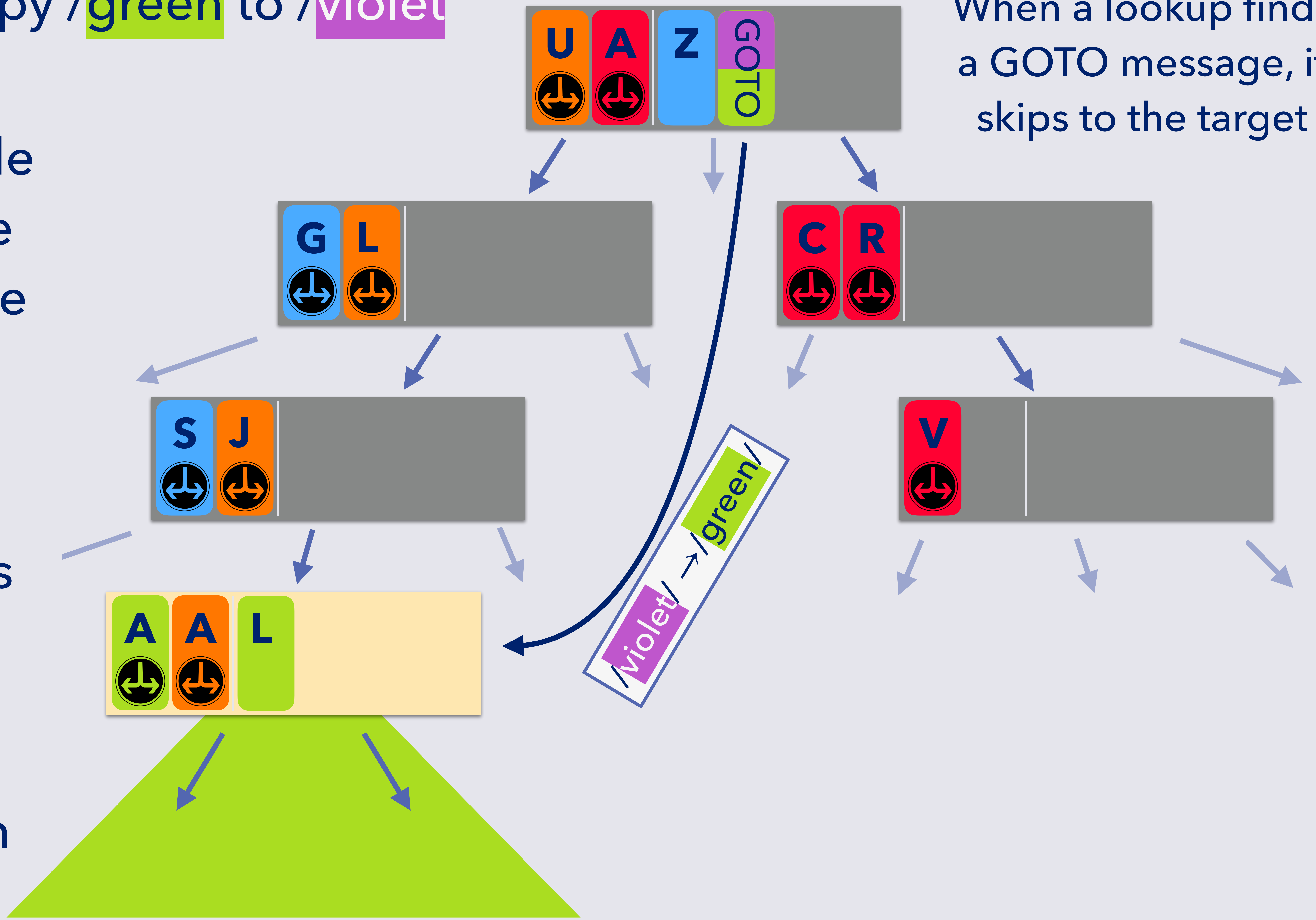

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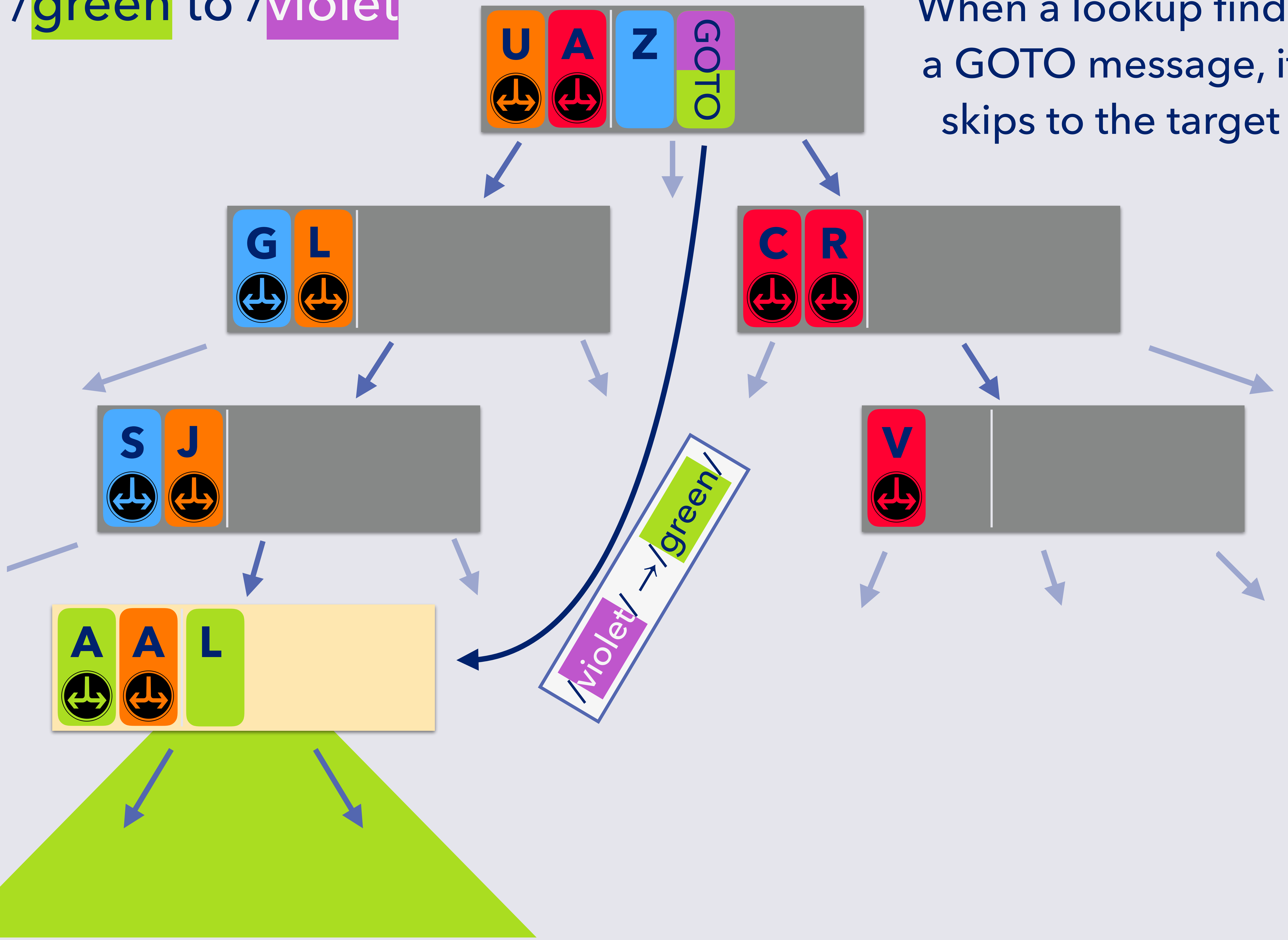

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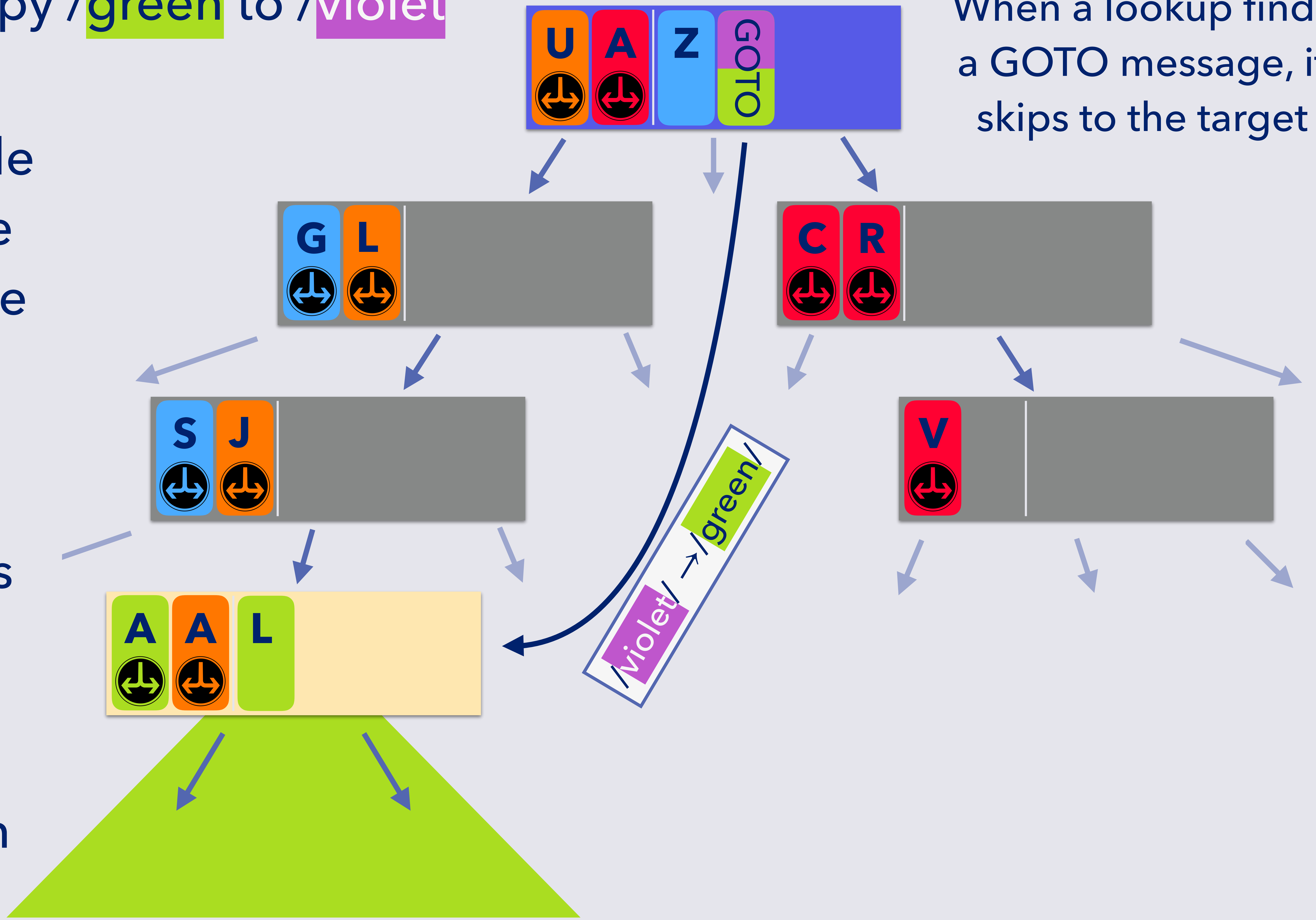

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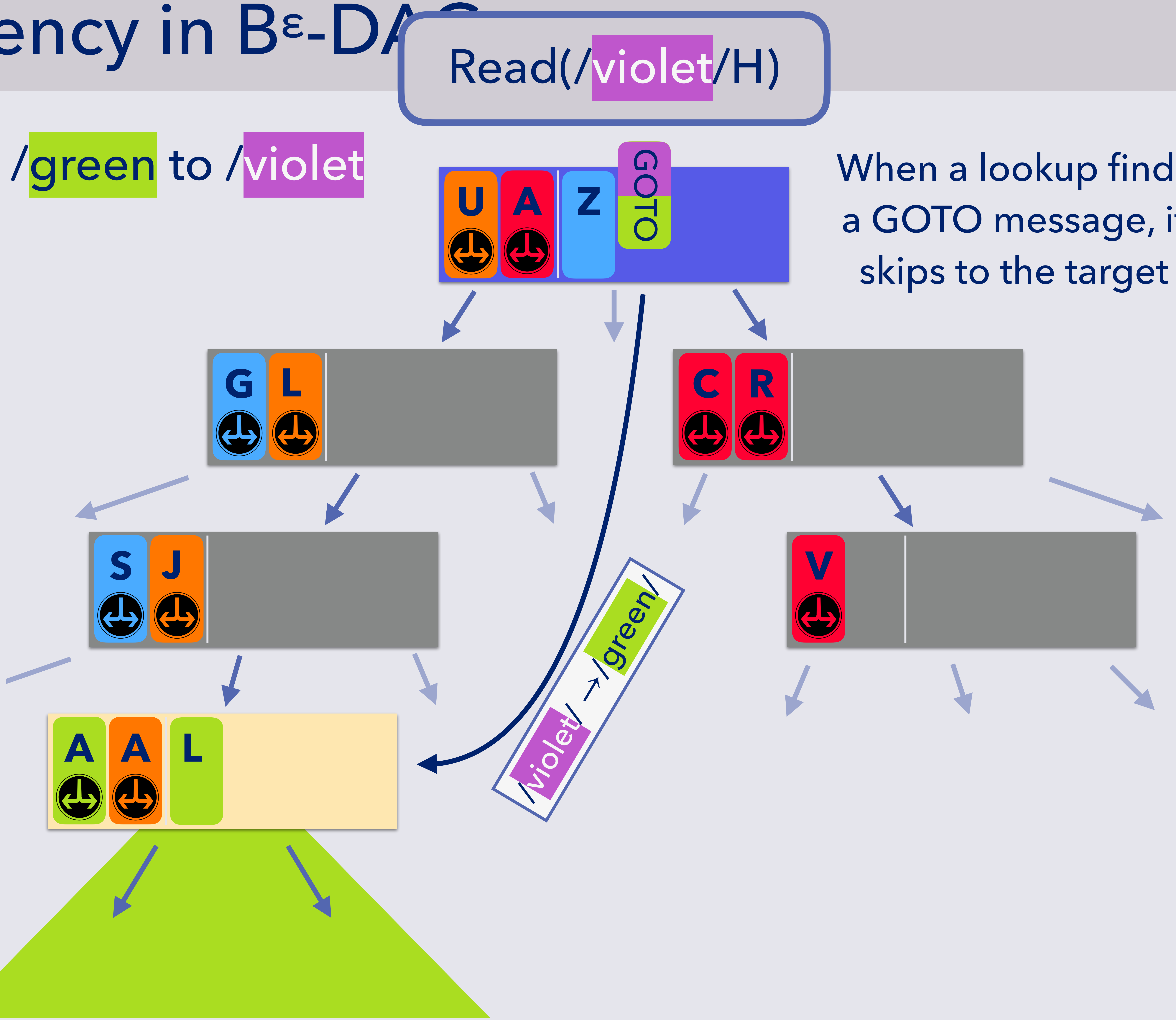

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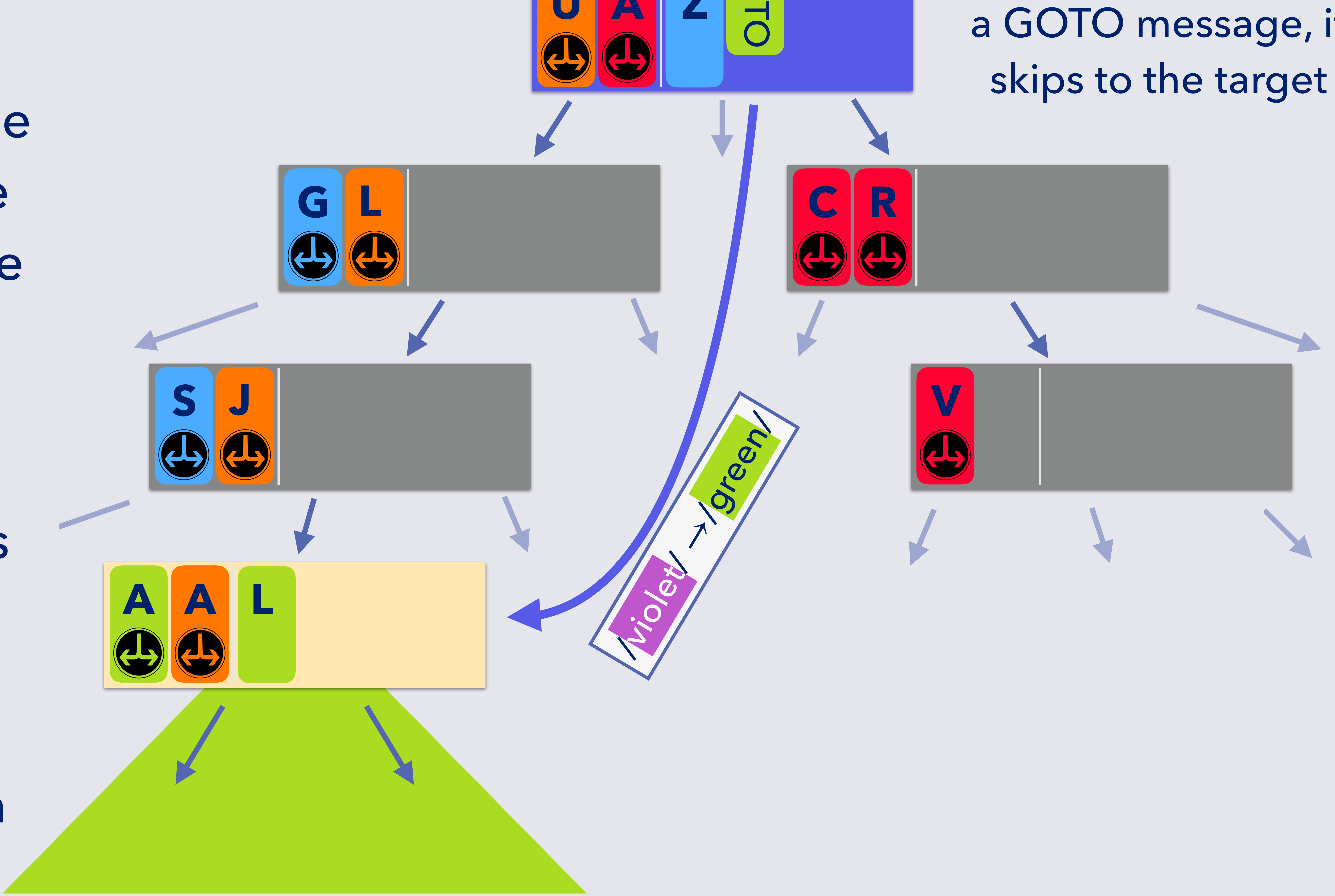

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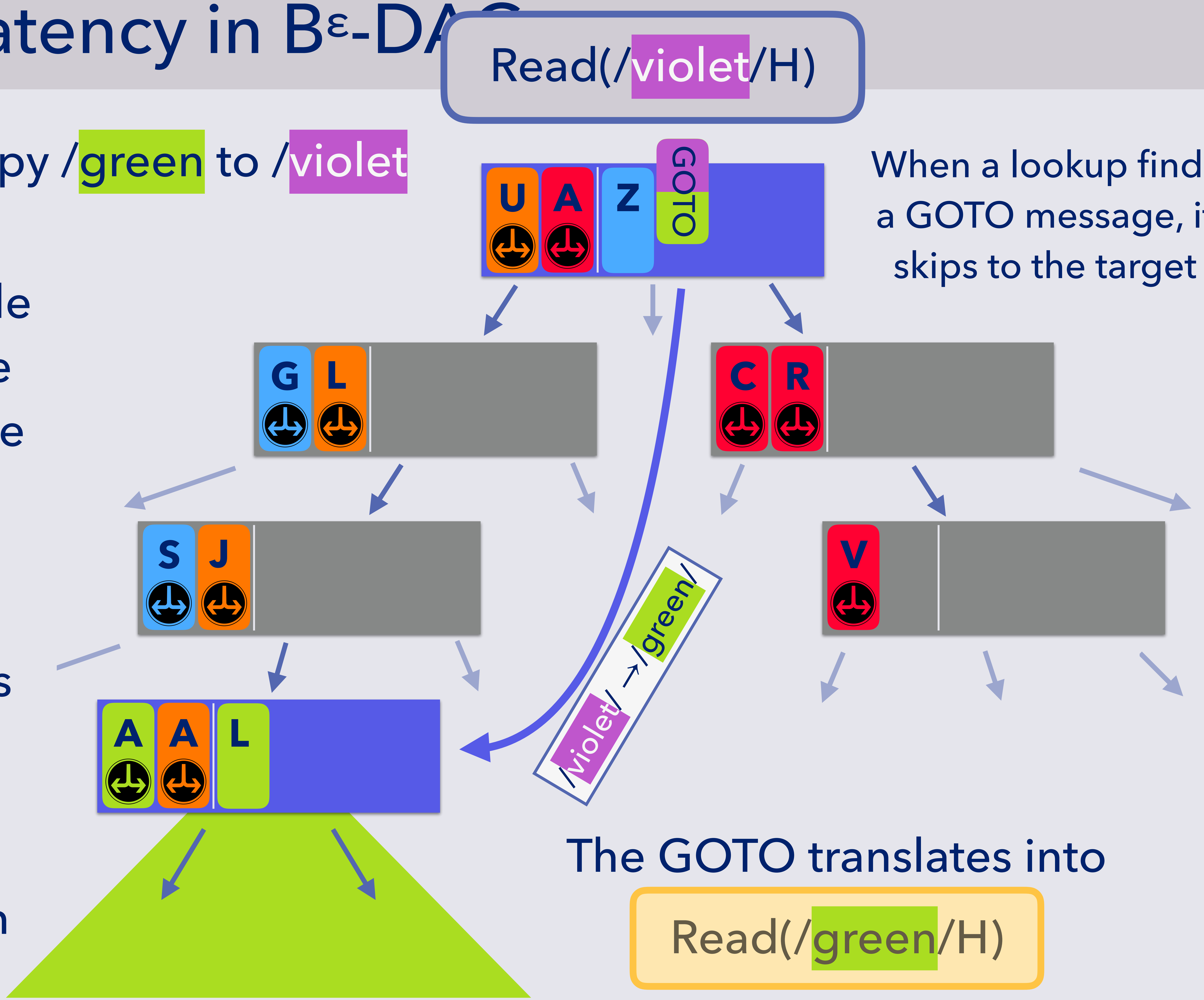

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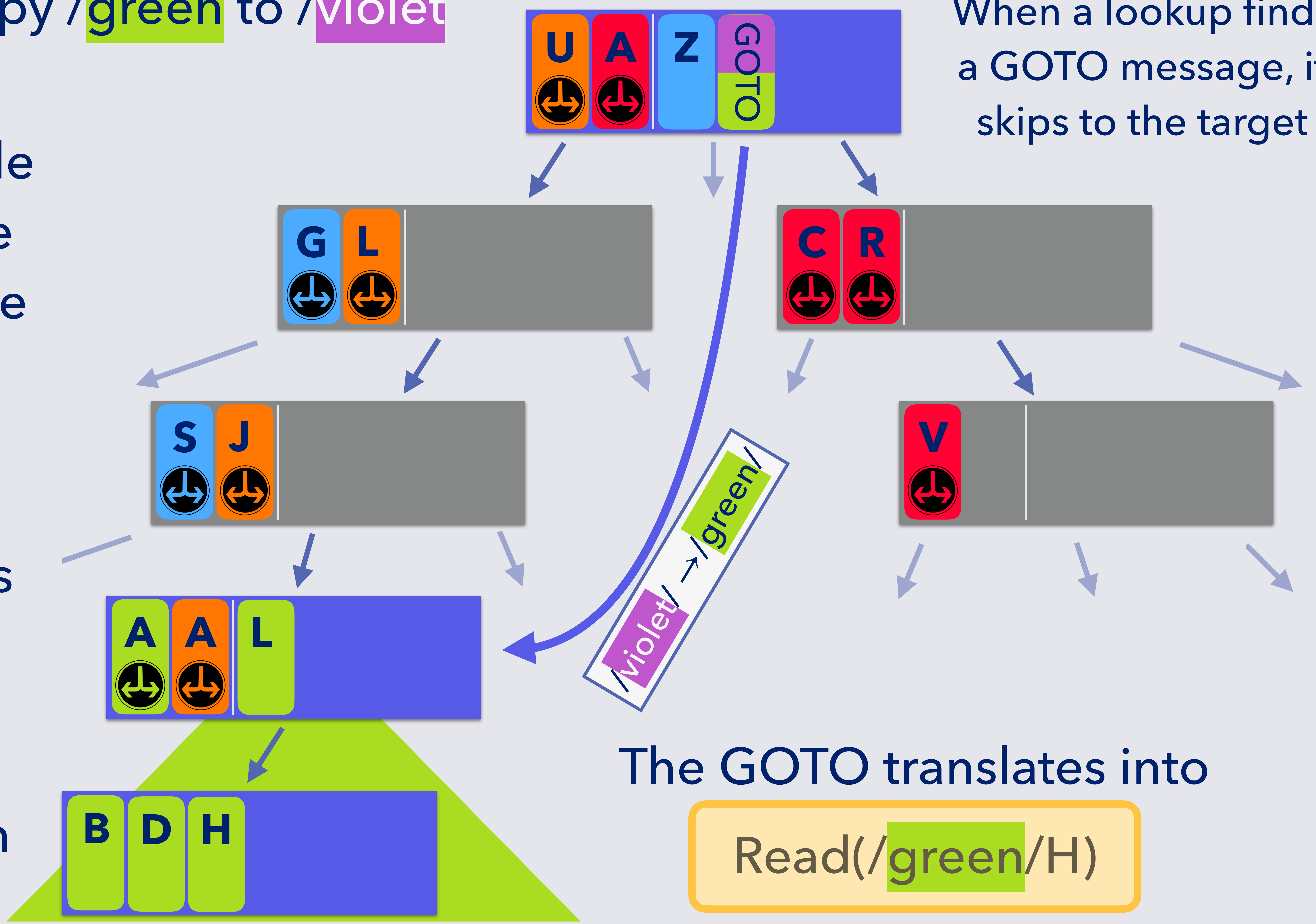

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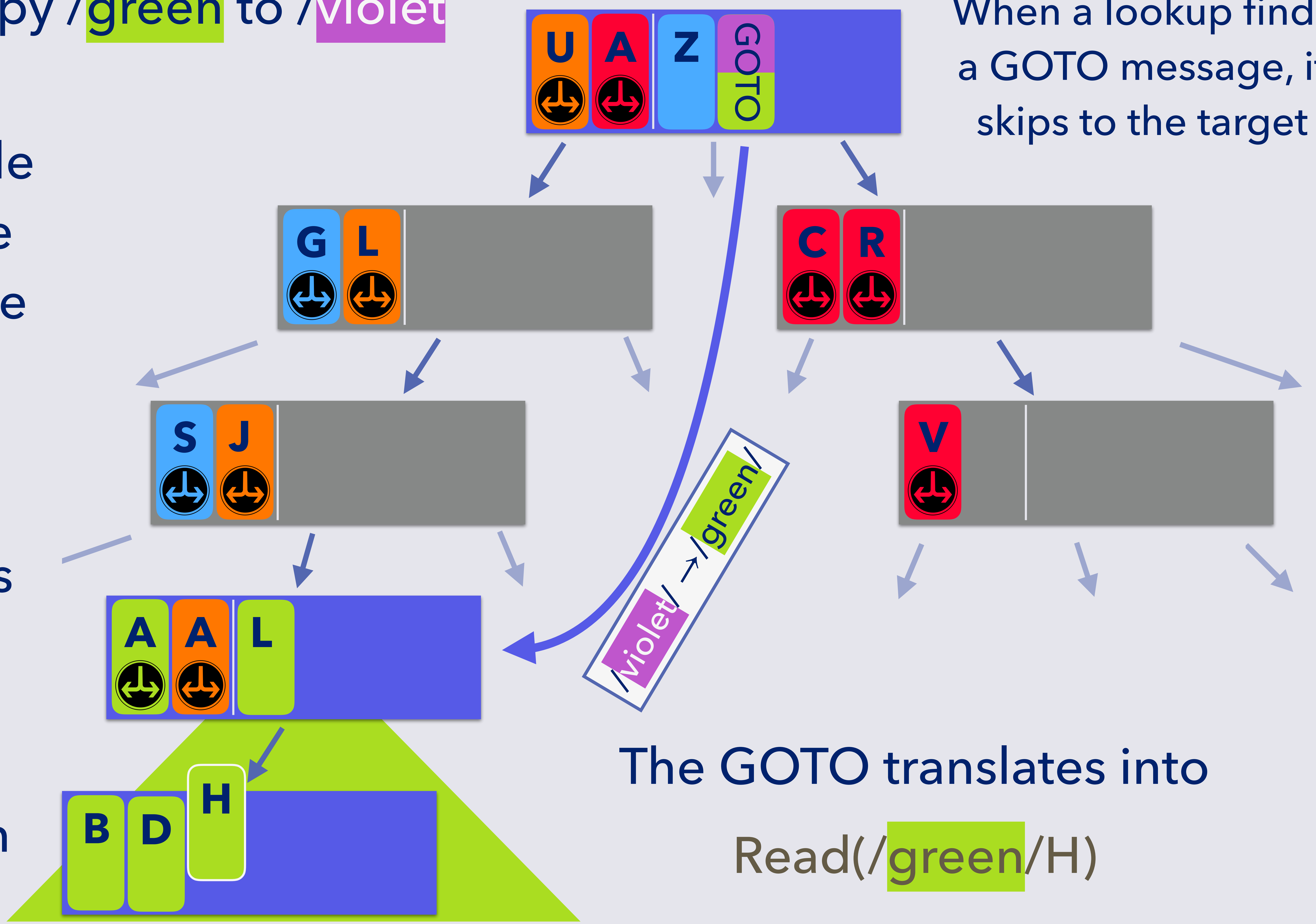

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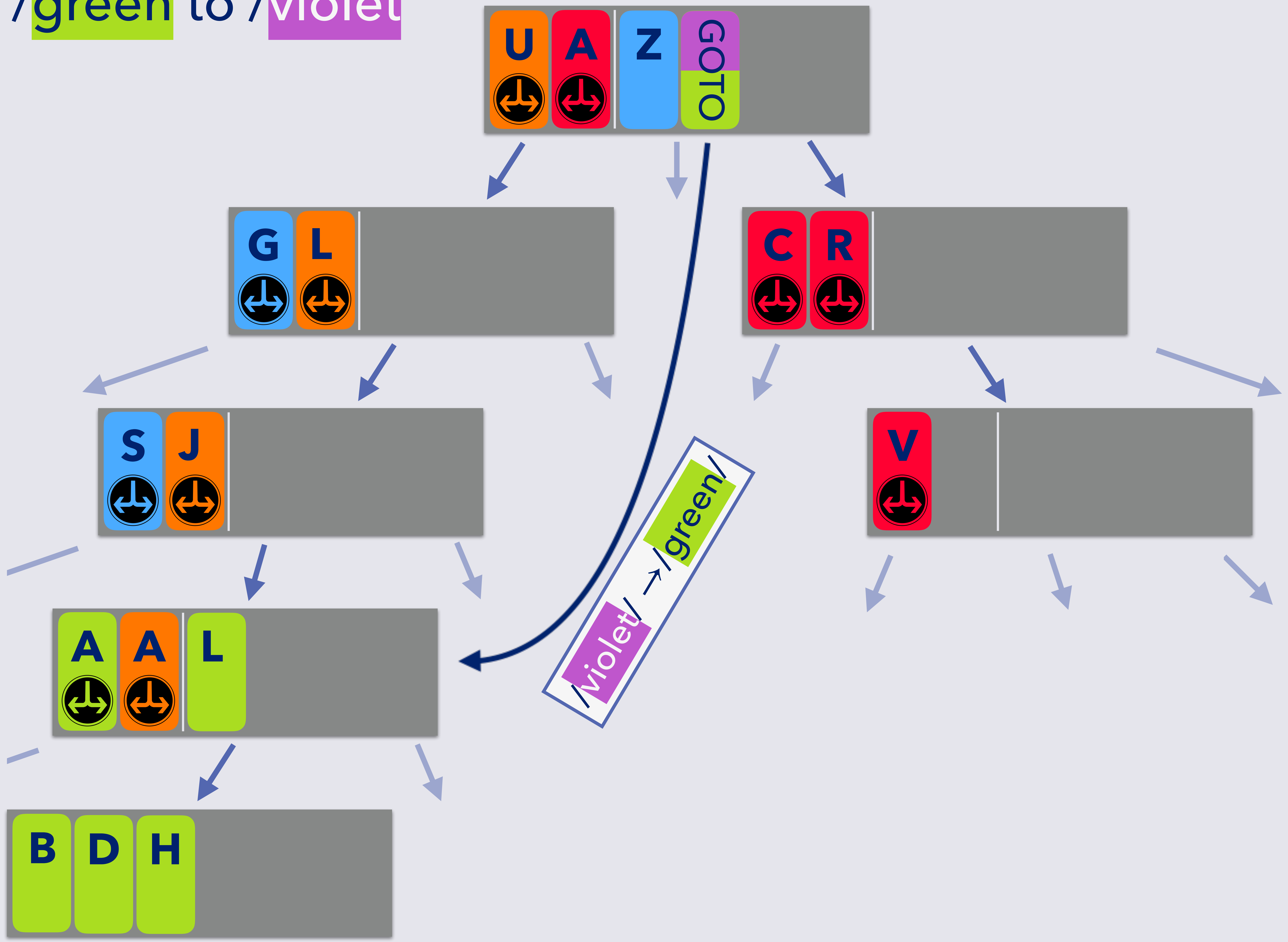

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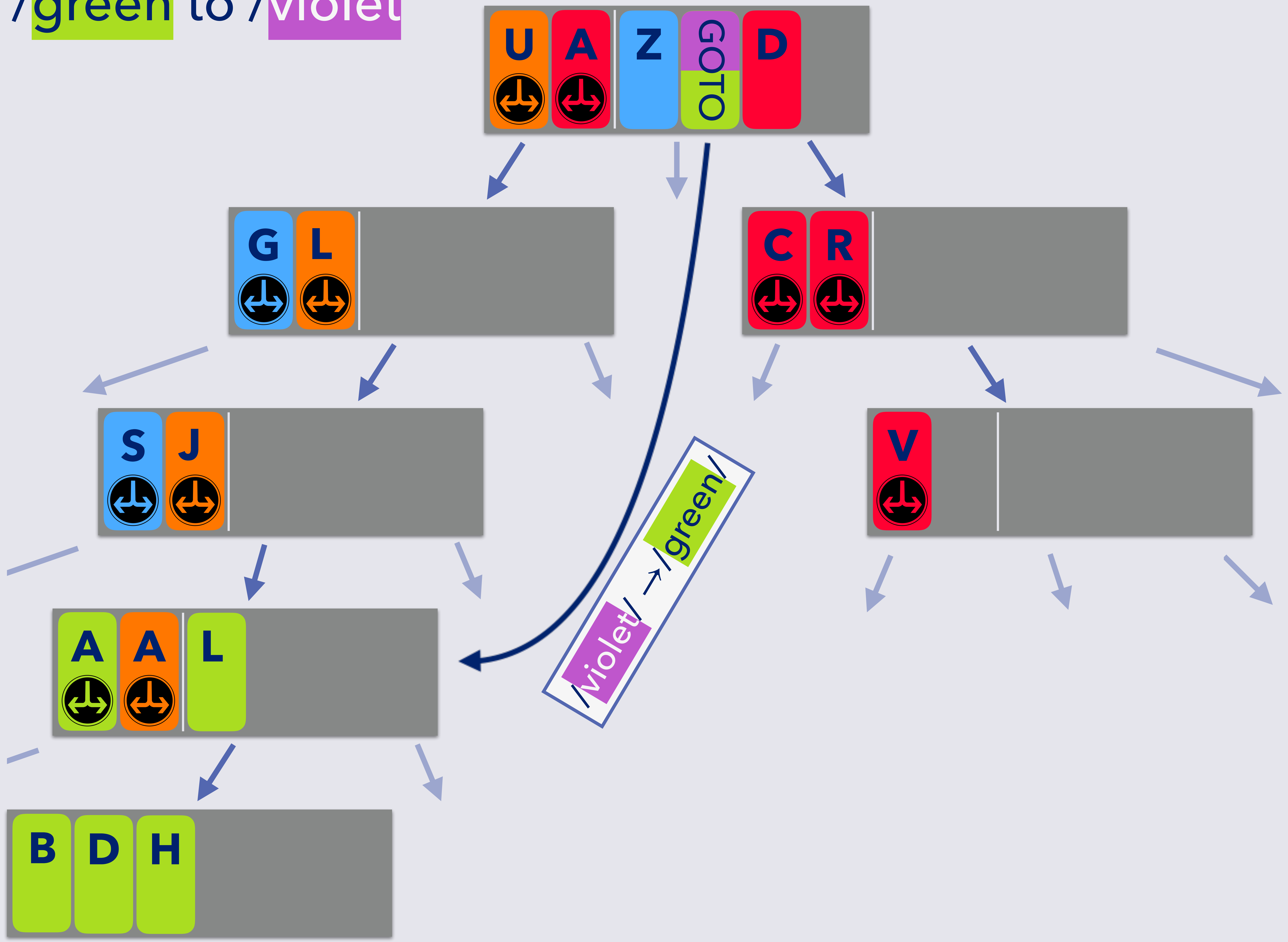

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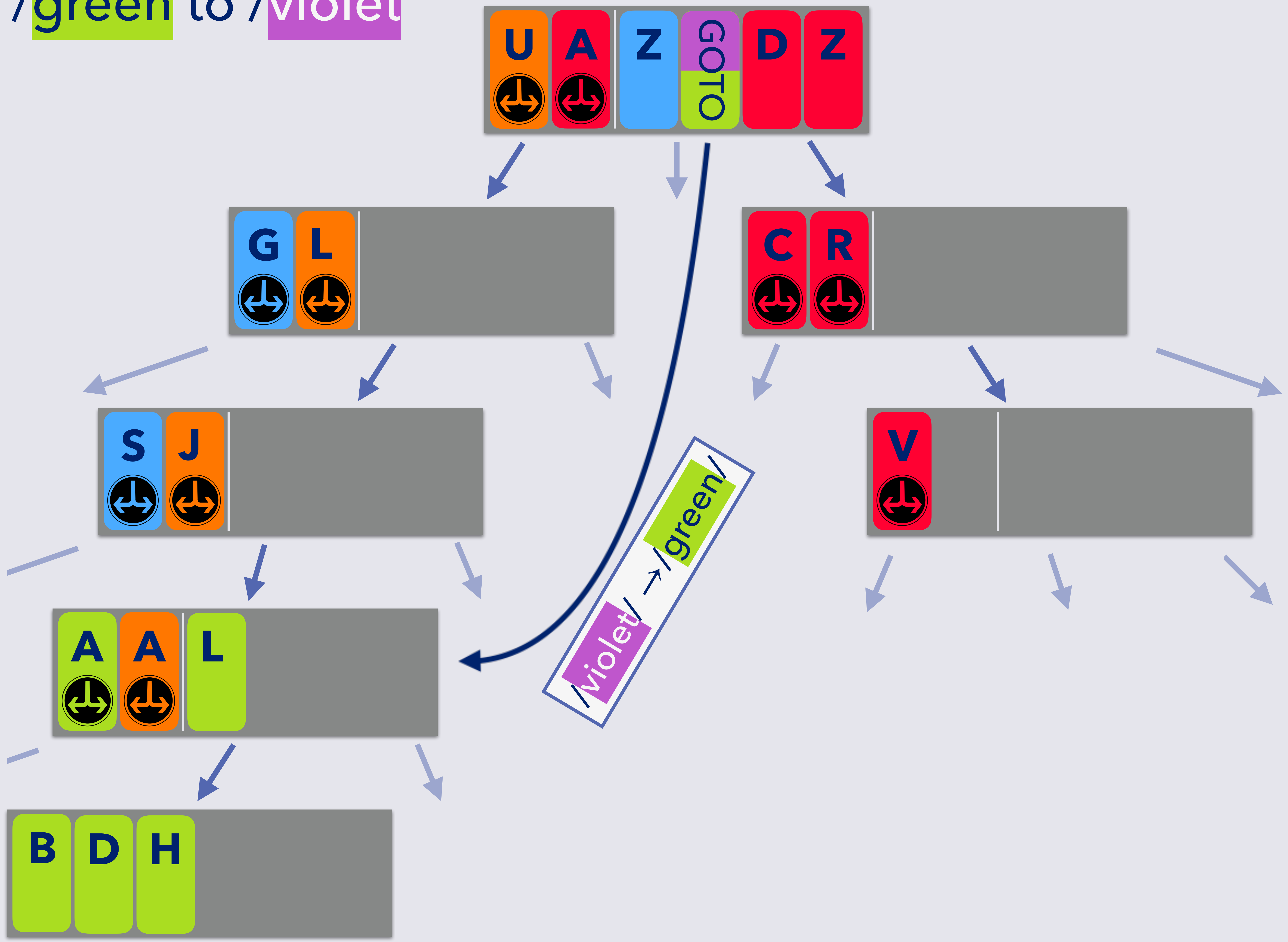

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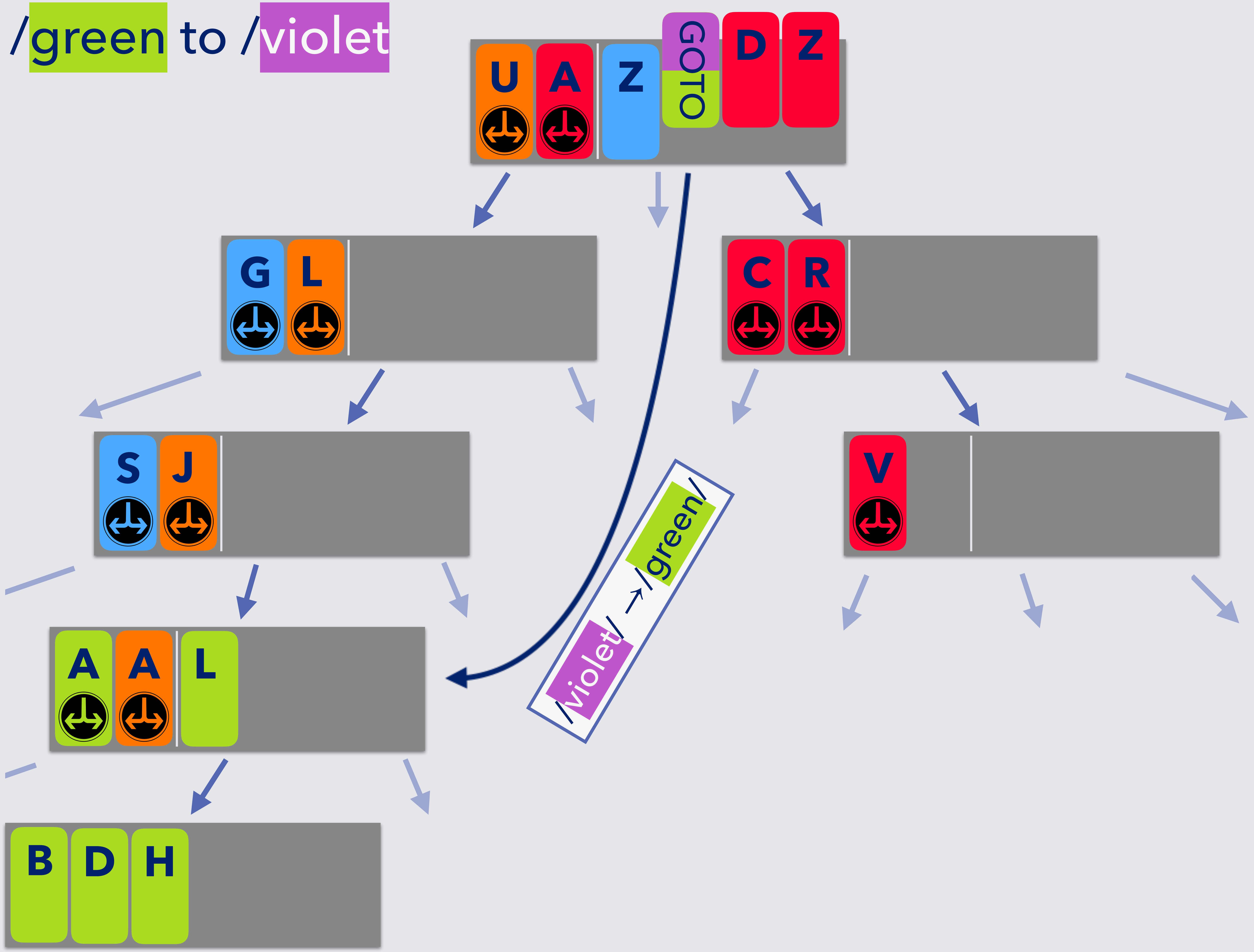

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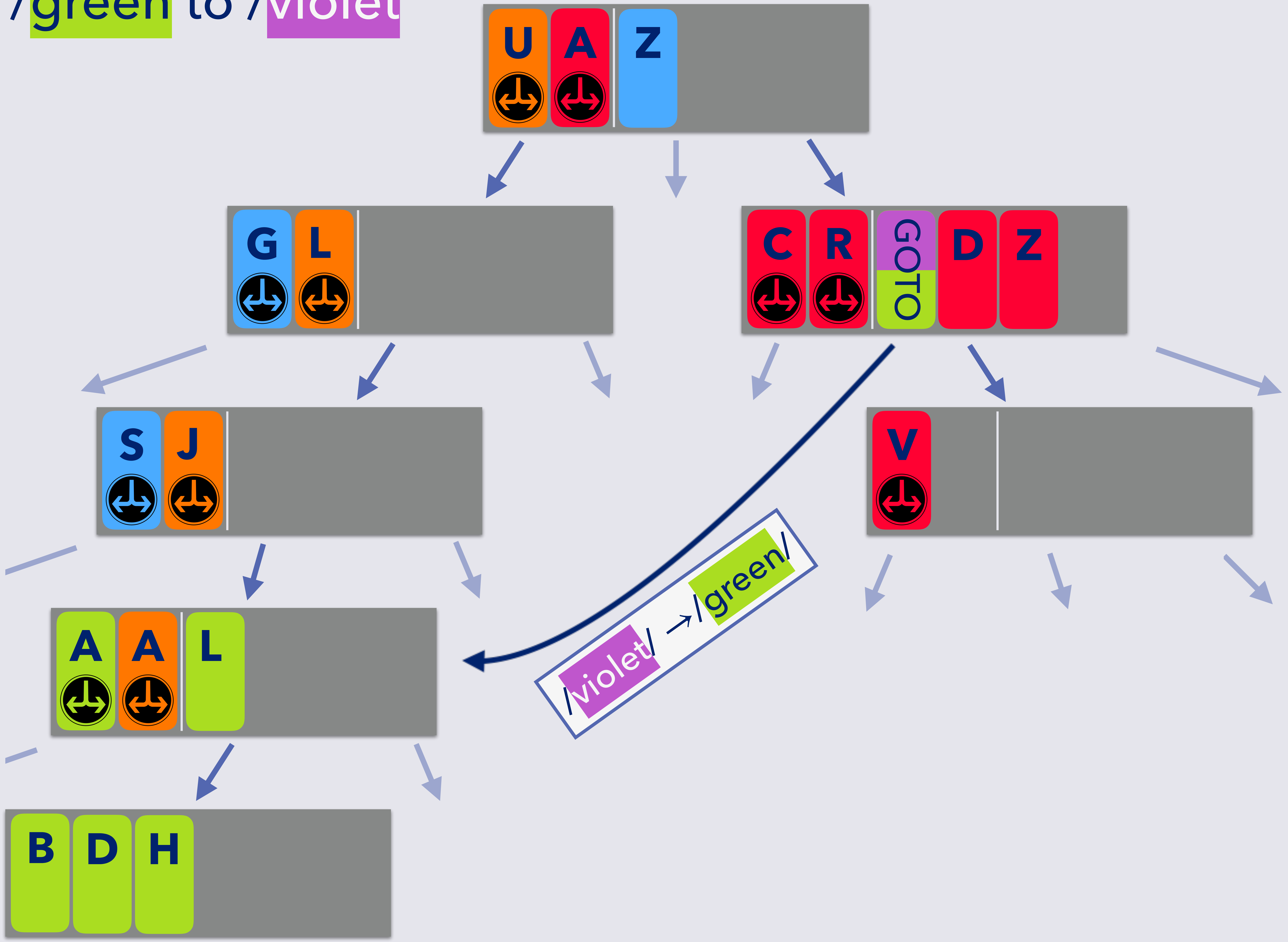

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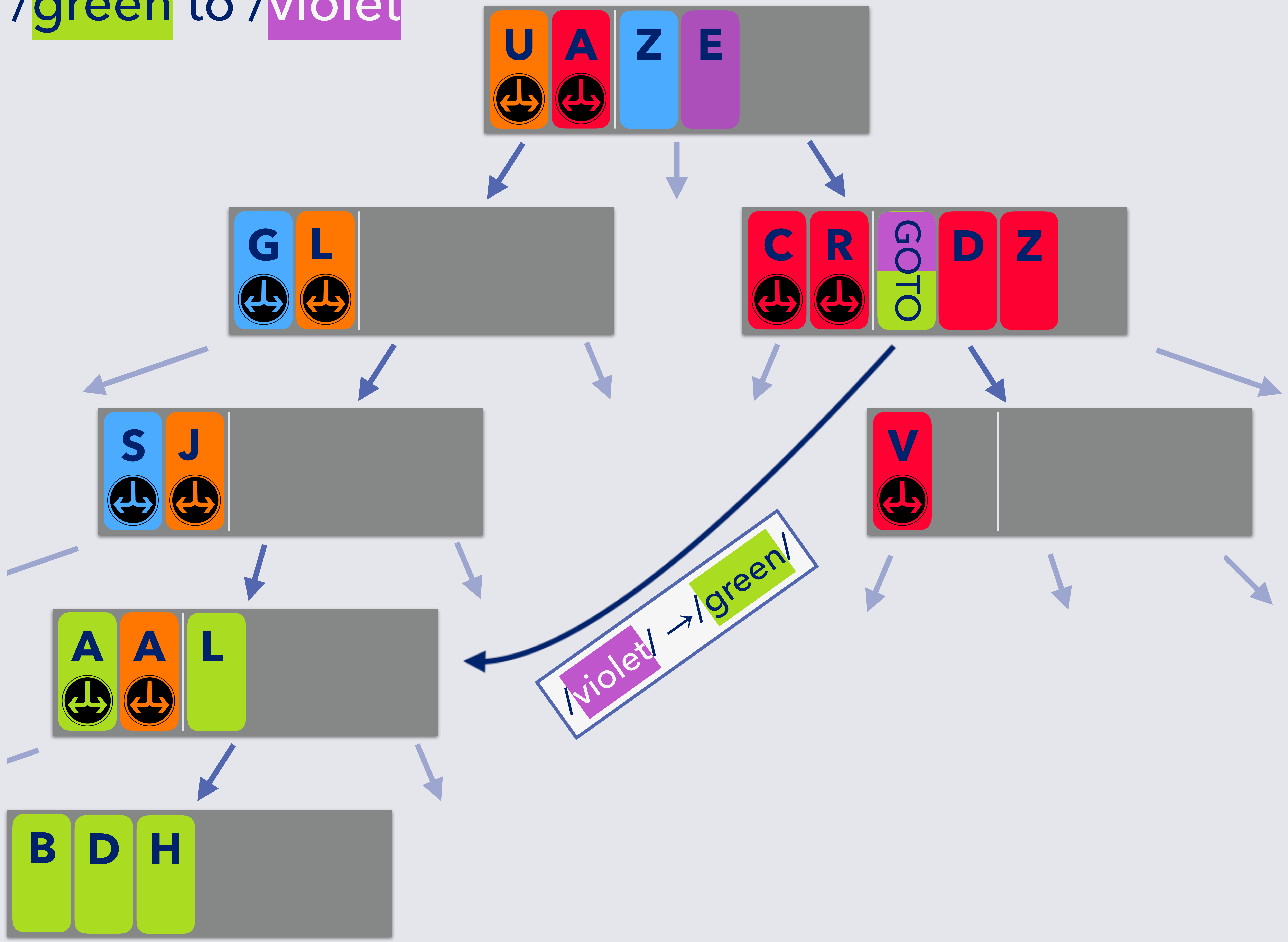

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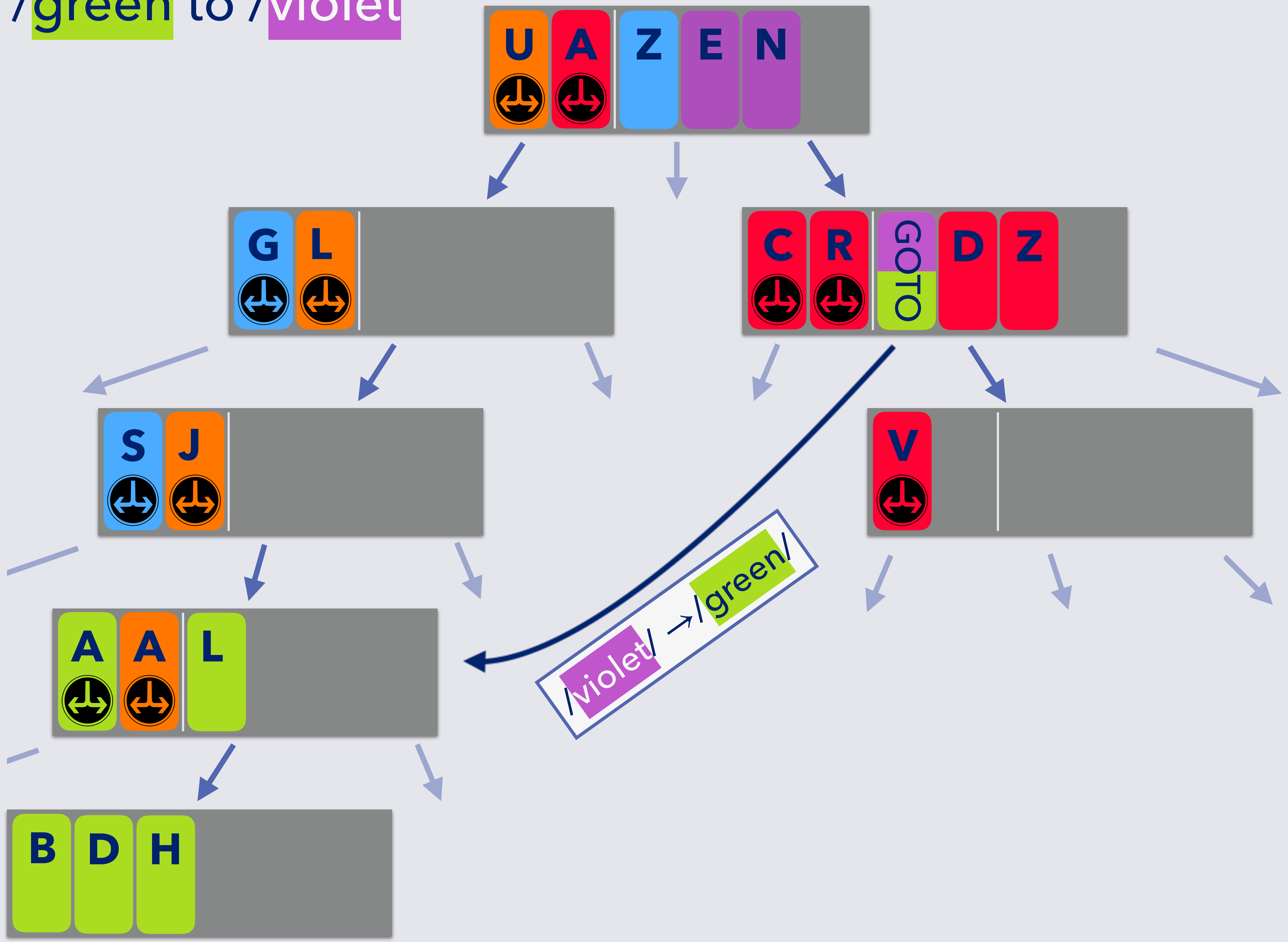

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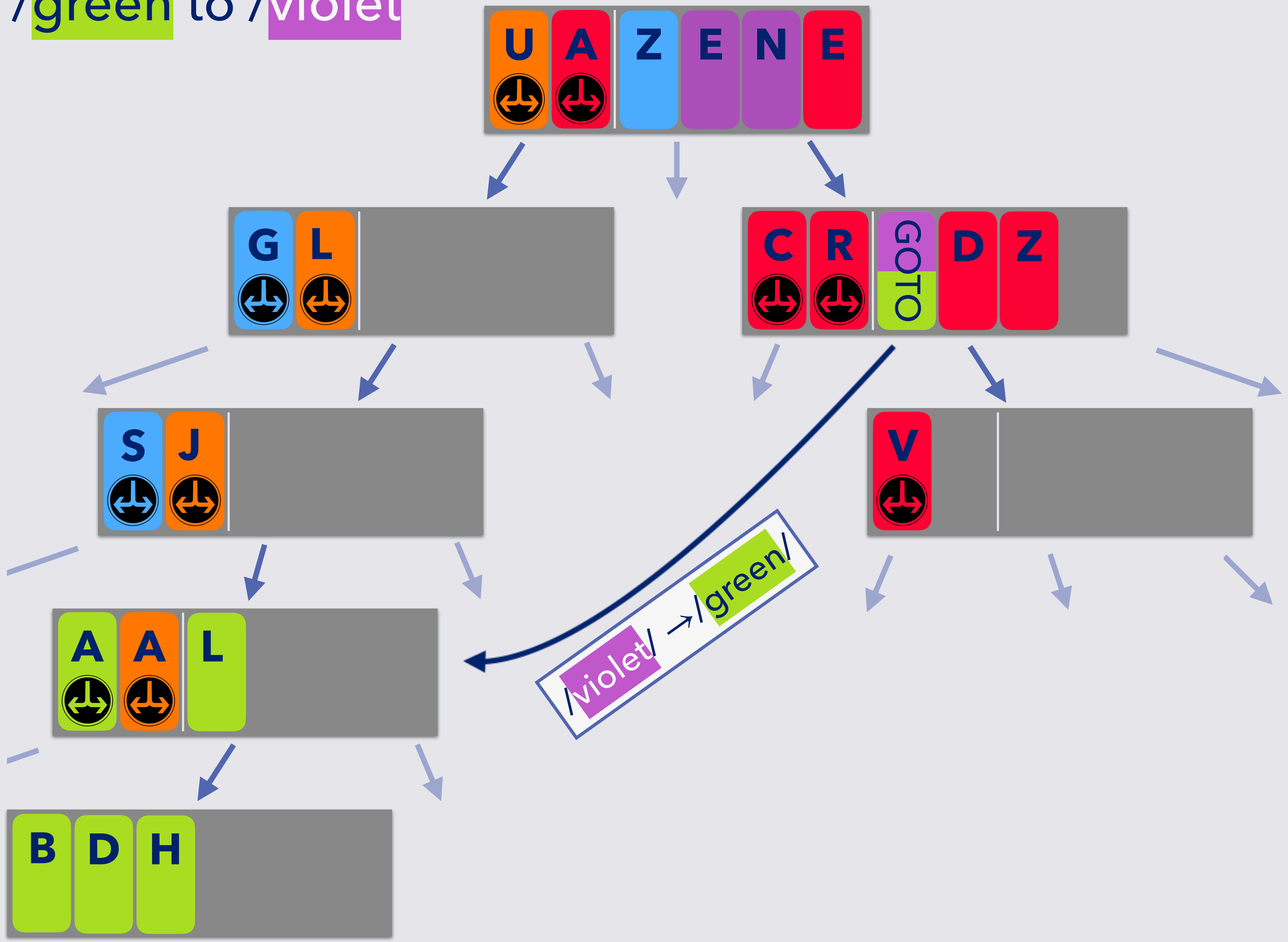

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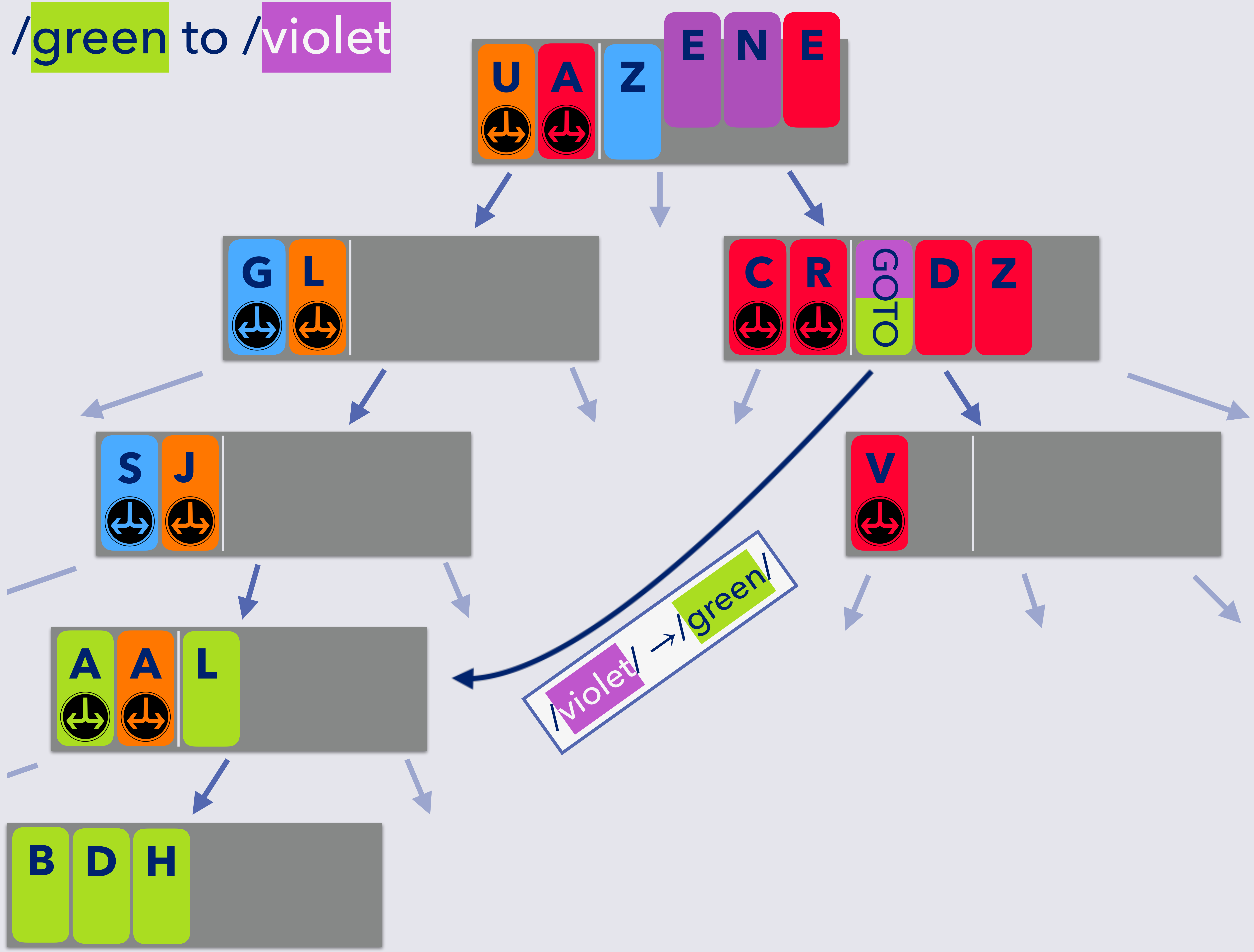

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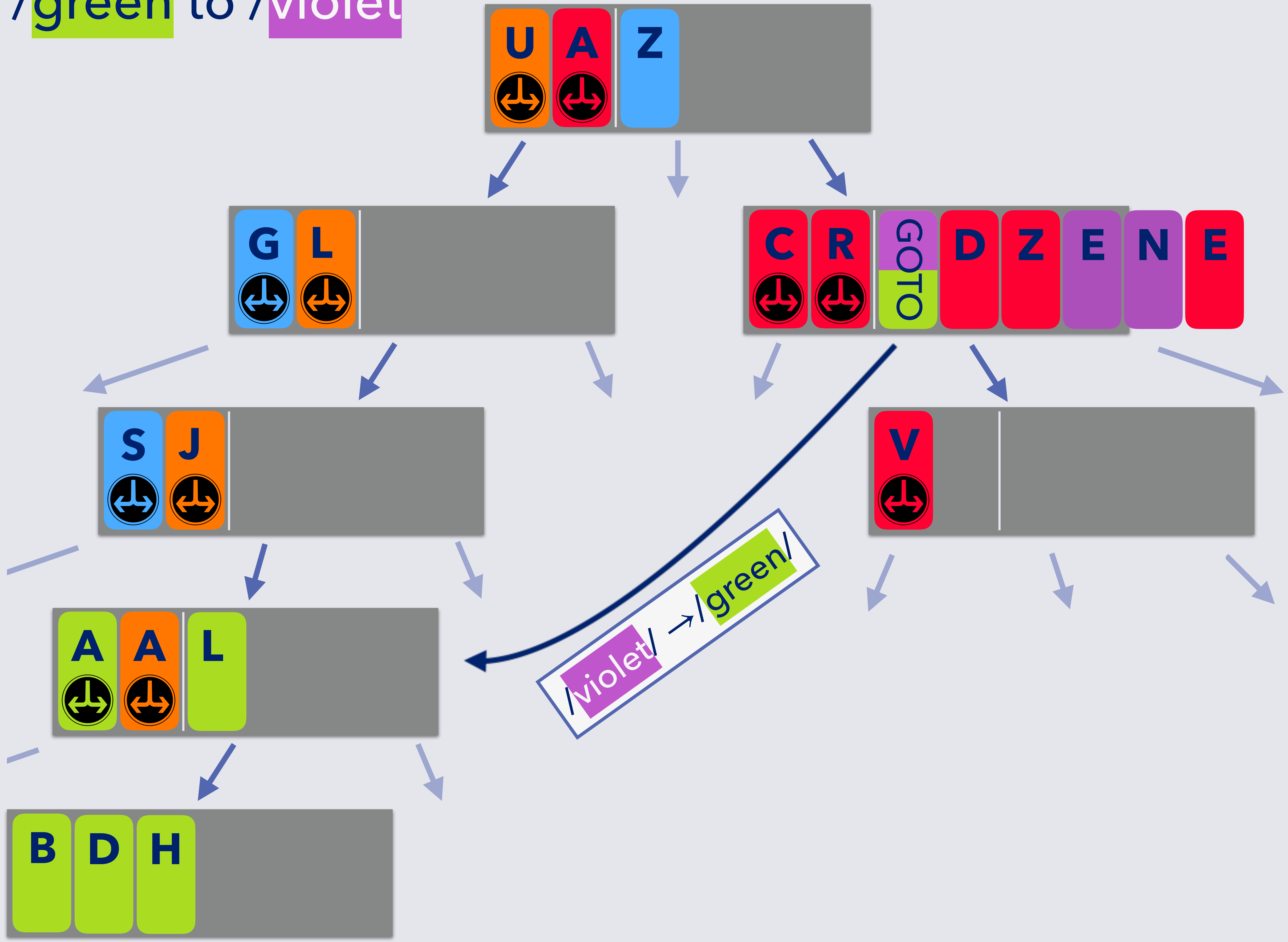

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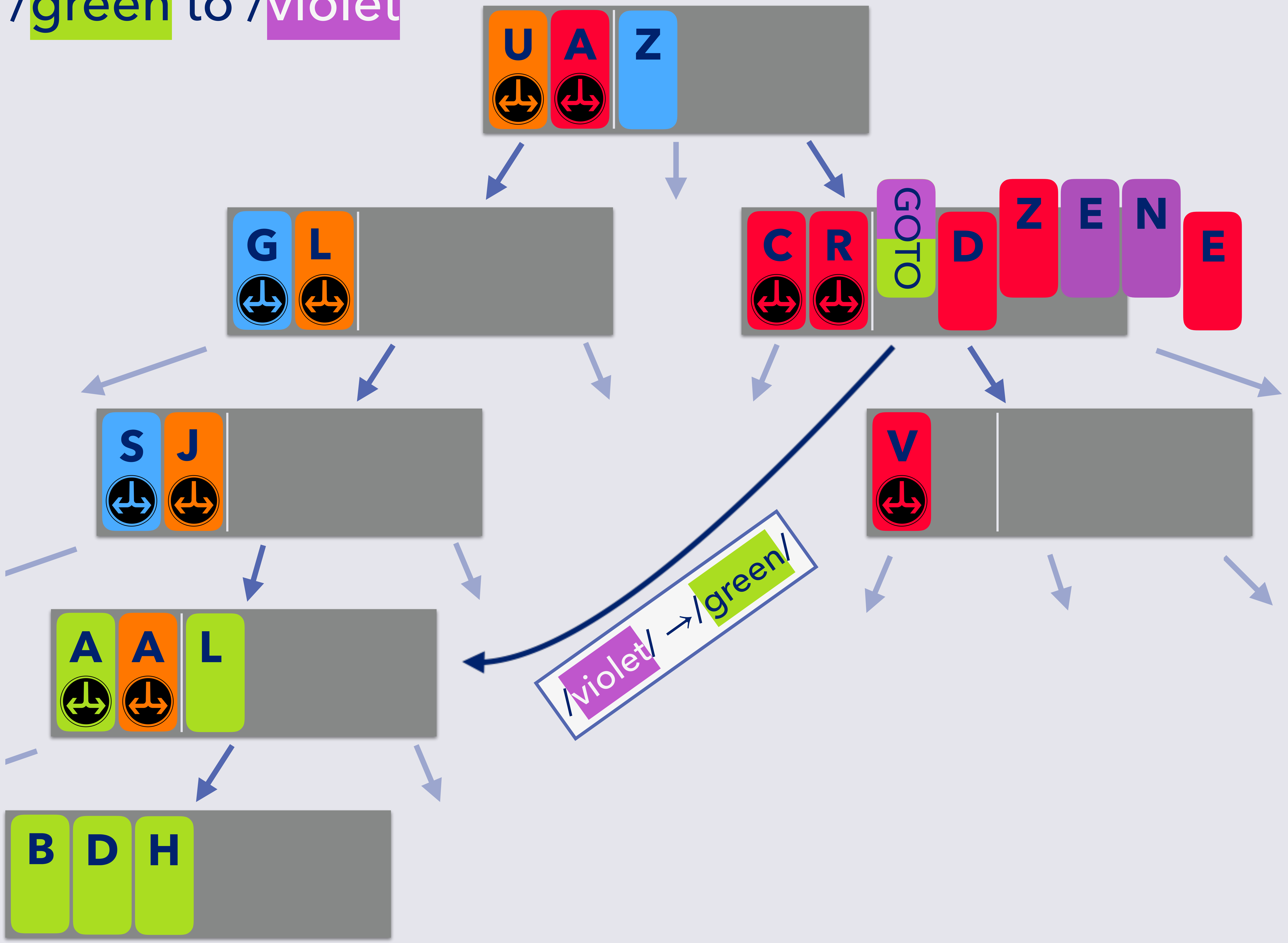

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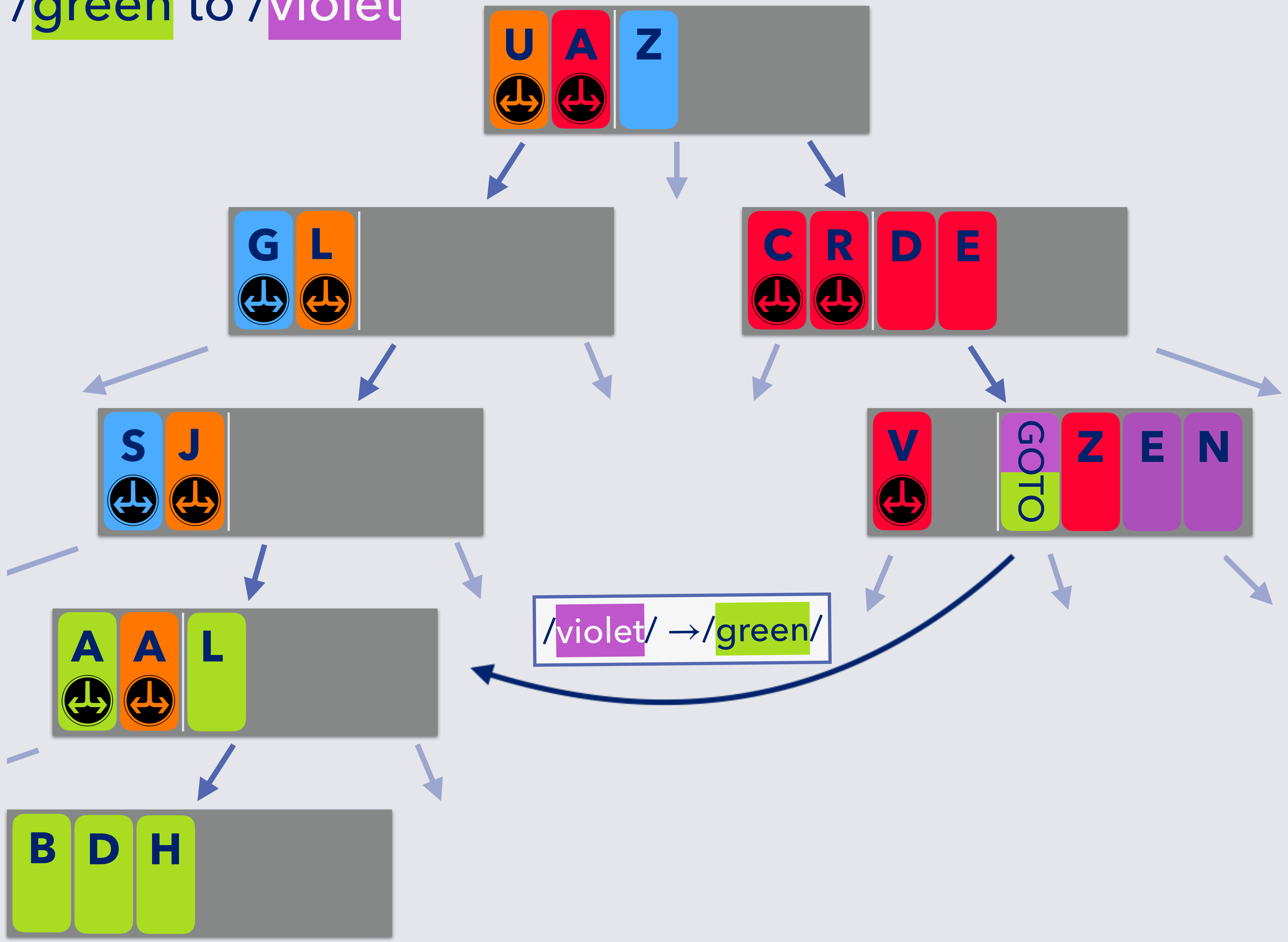

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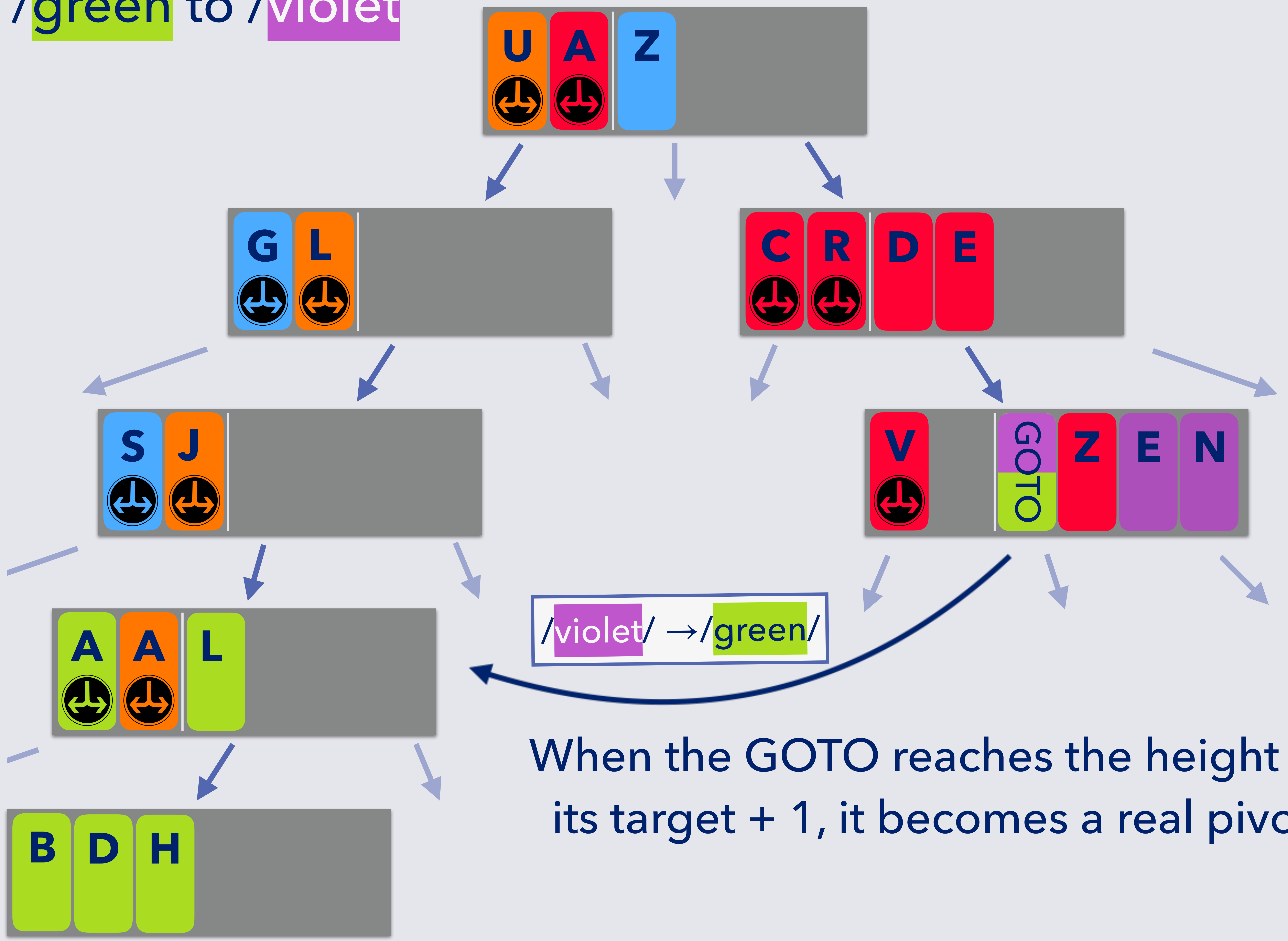

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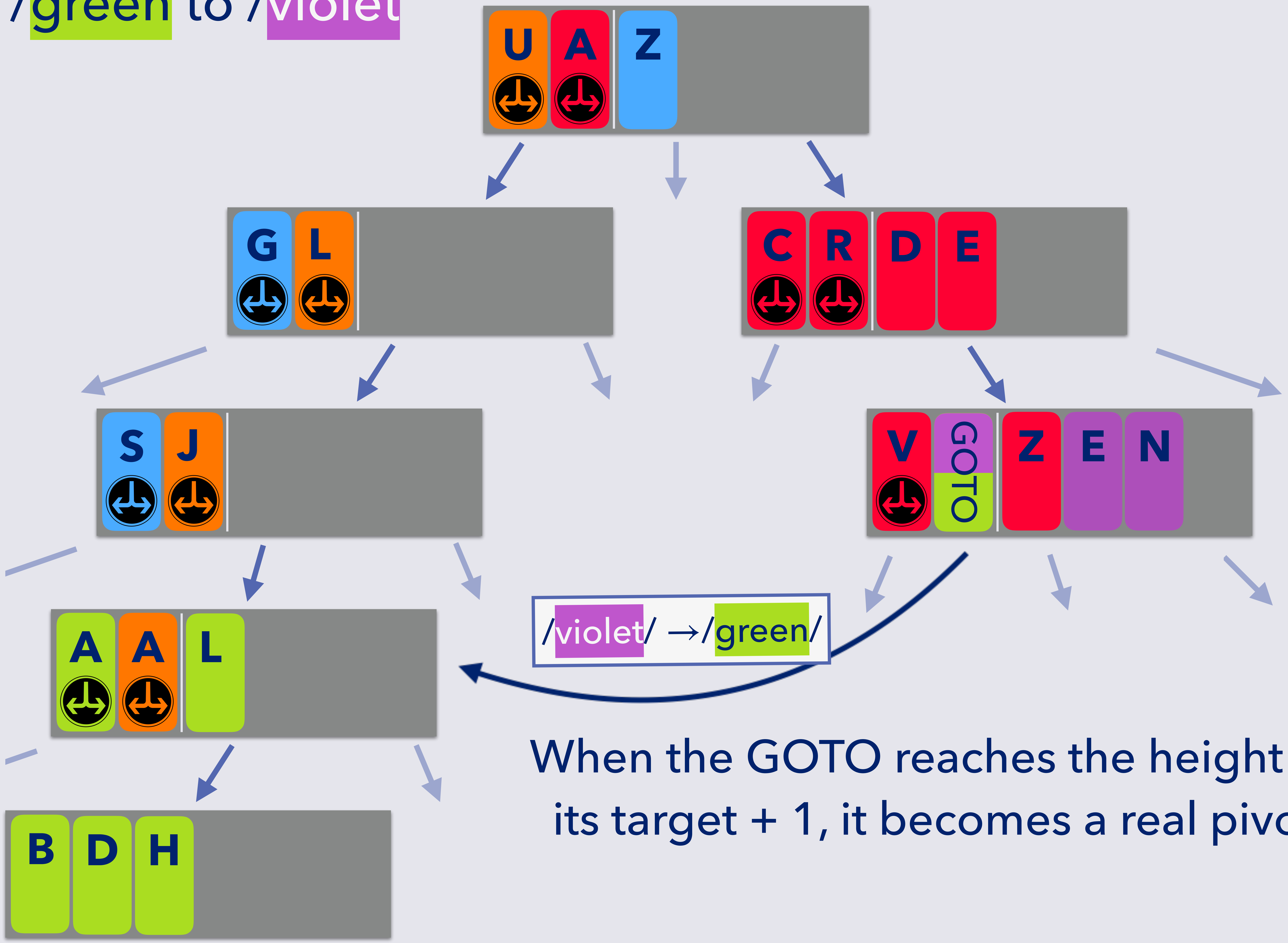

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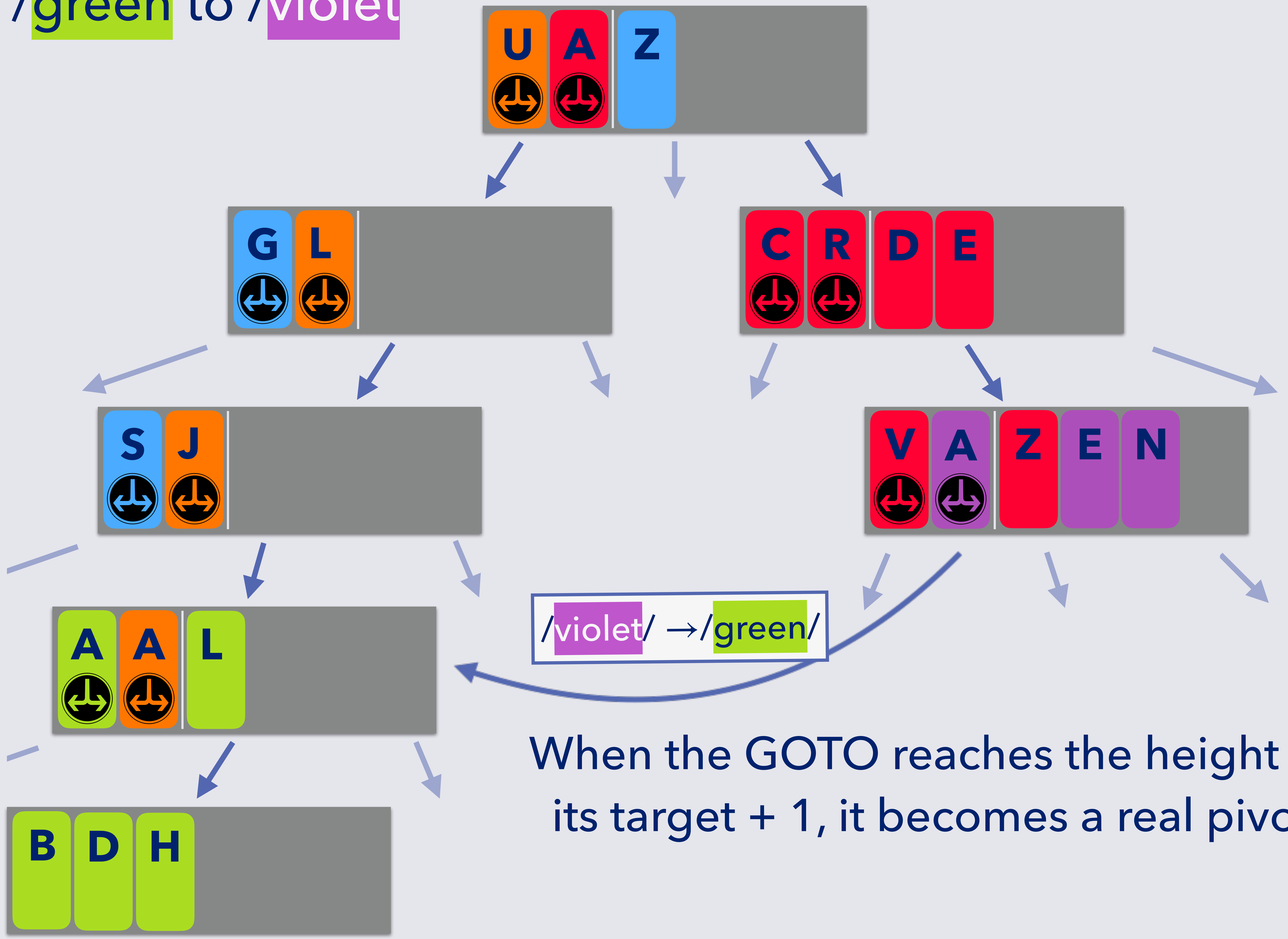

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Copy-on-Abundant-Write

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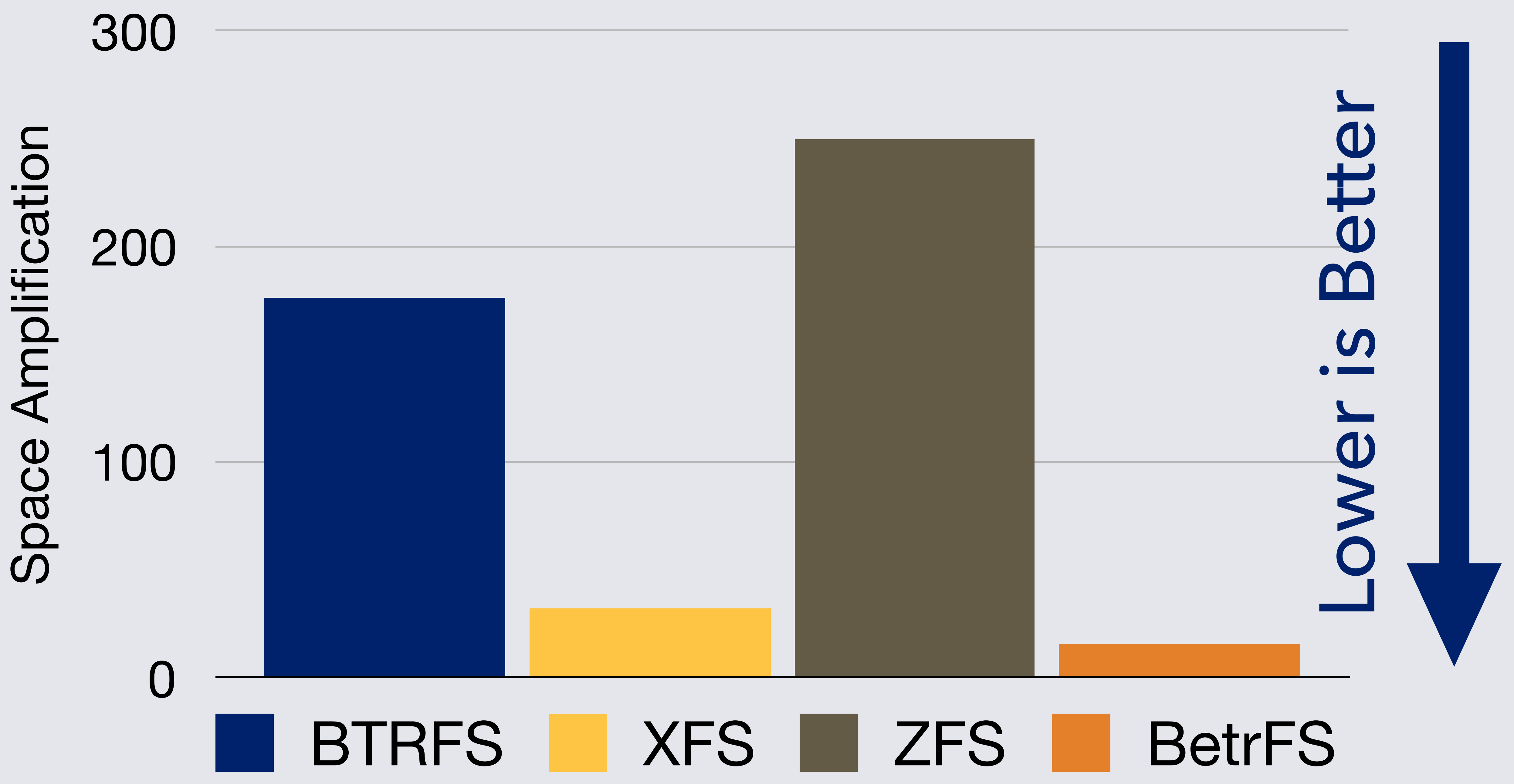
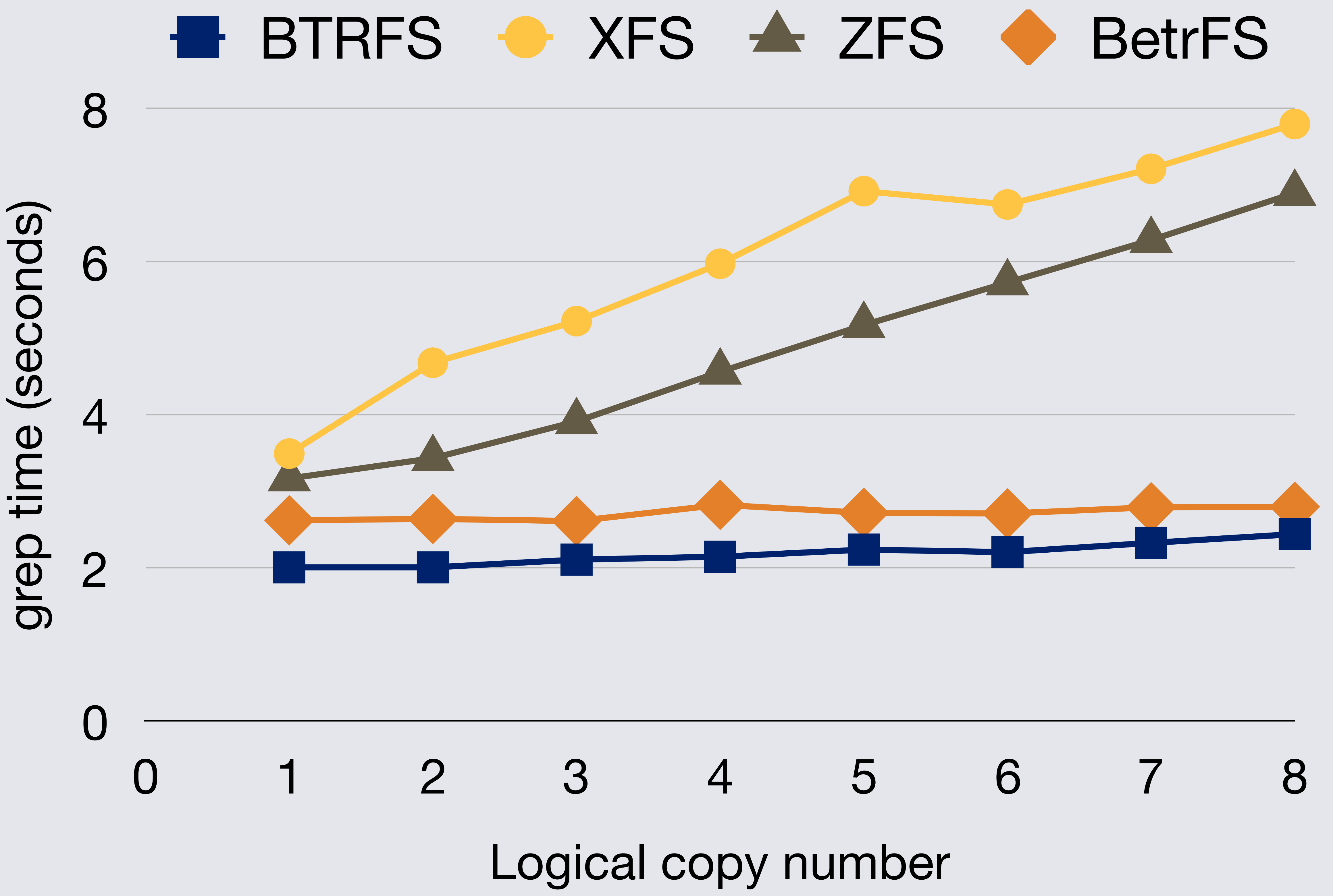
Evaluation

Space Amplification and Fragmention

Dell Optiplex 790
4-core 3.40 GHz Intel Core i7 CPU
4GiB RAM
500GB 7200 RPM SATA disk

Init: 64 4MiB files with random data.
Each round: logically copy all files, then change 16B in each file (1KiB total)





Space Amplification
additional file system size / added data (1KiB)

Fragmentation
measured by timing a grep over the file system

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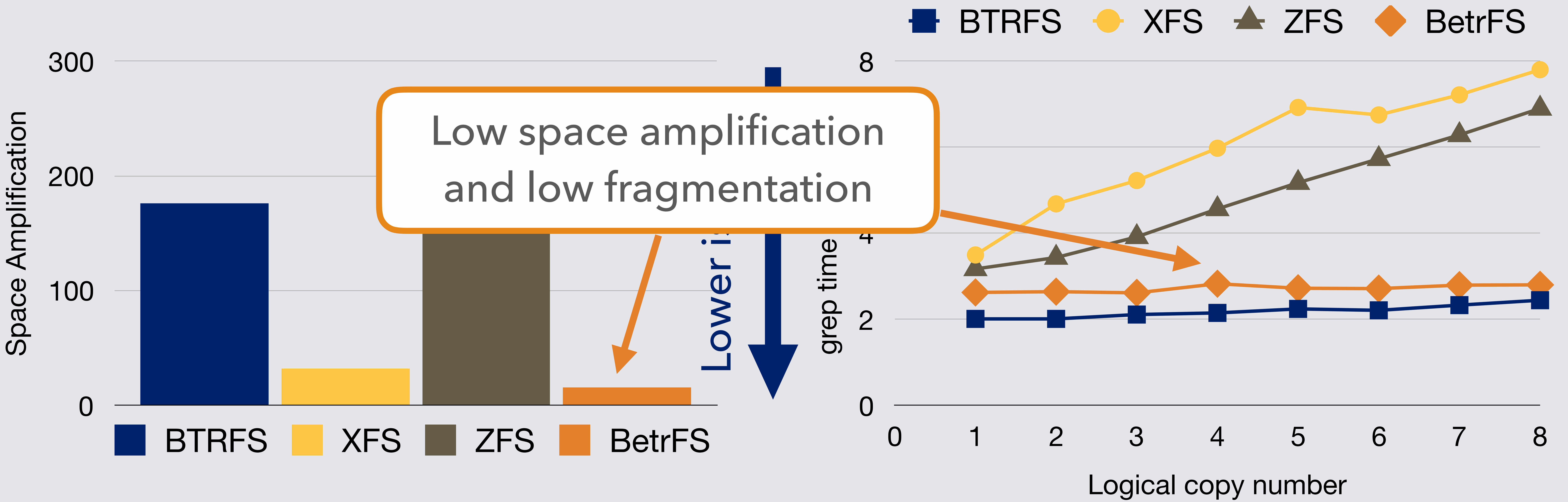

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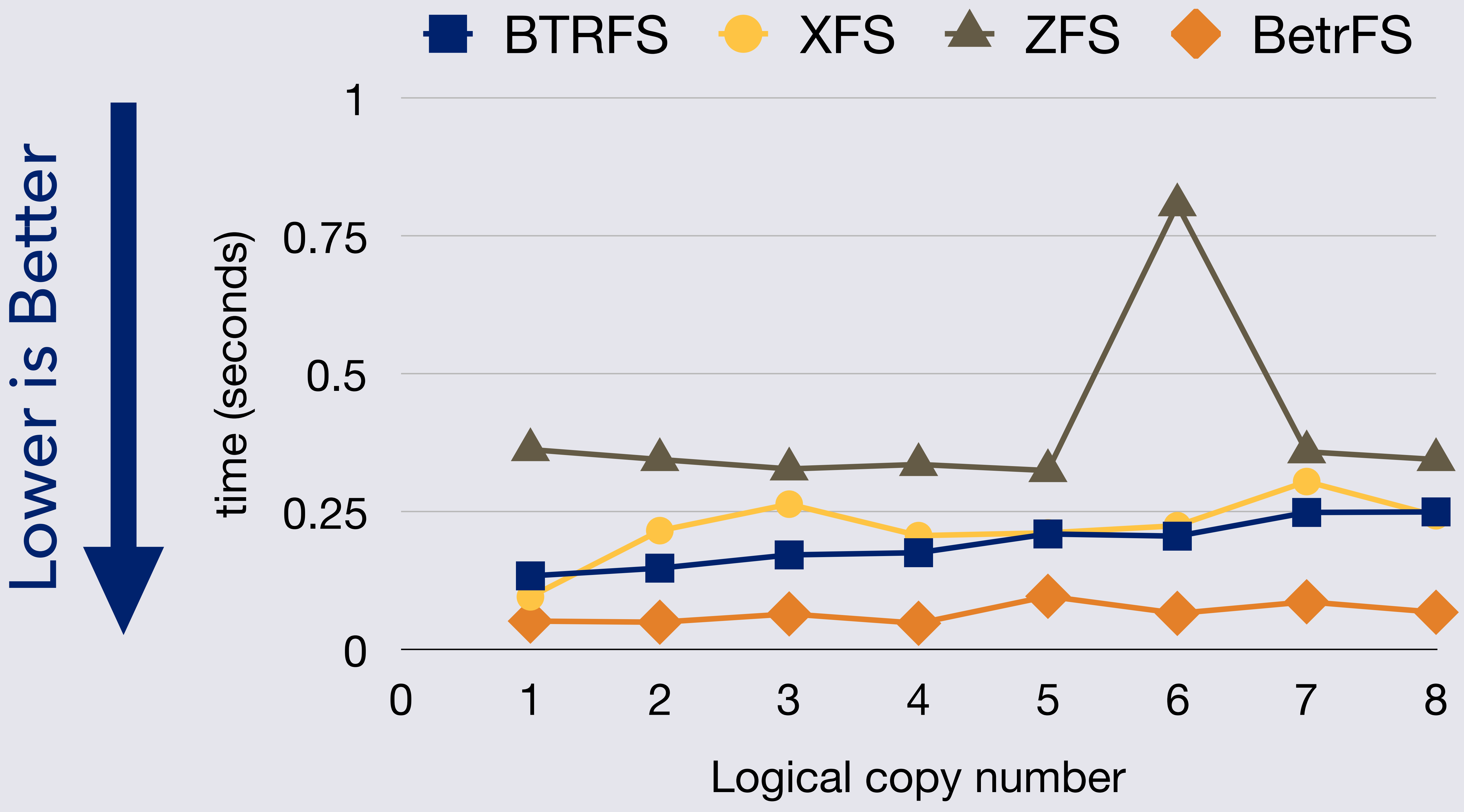

Copy Latency

time to perform the copy

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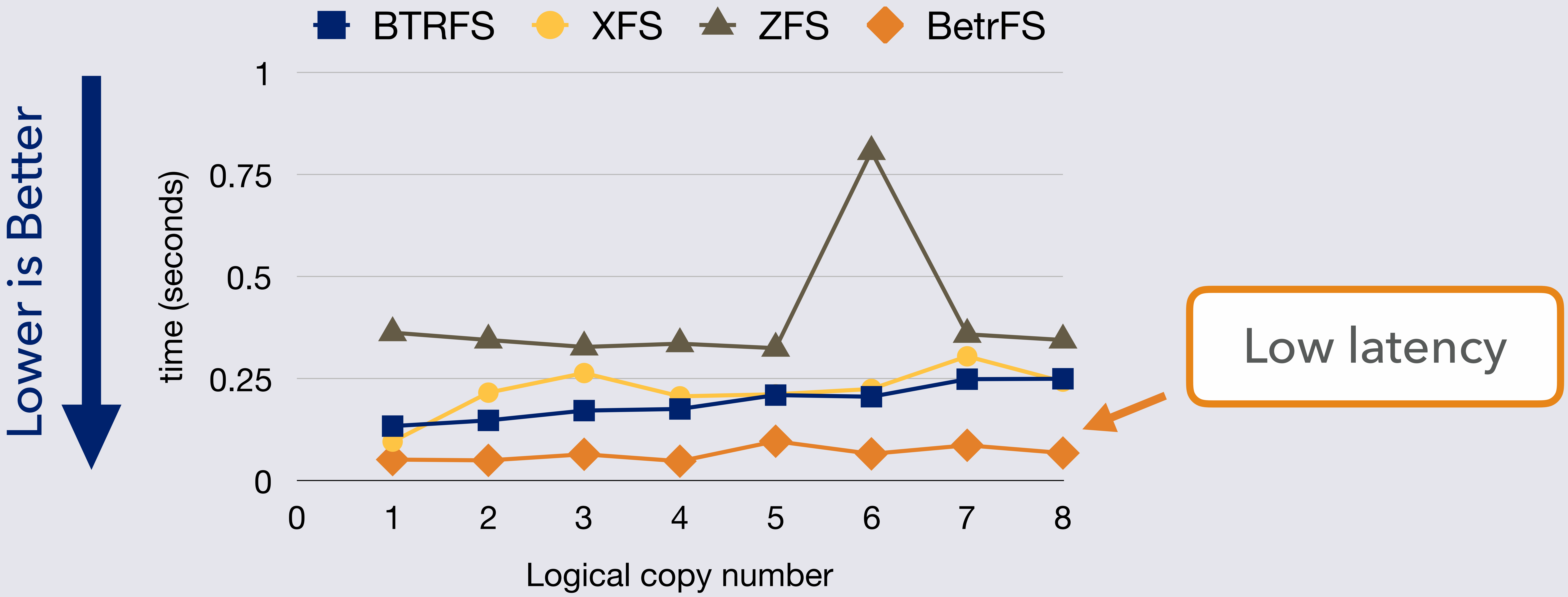

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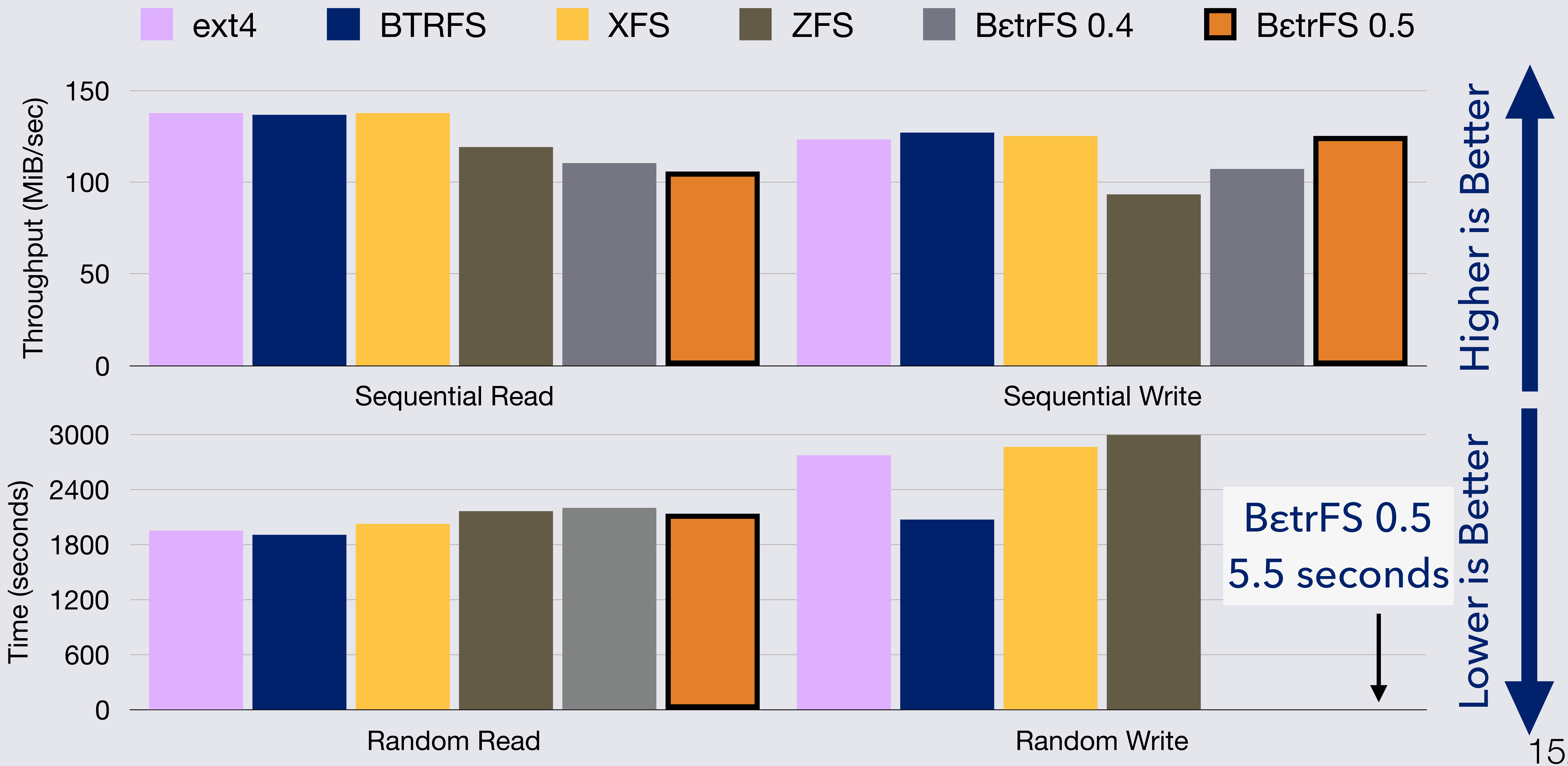
General File System Microbenchmarks



Application Benchmarks

Technical Conclusions

B$^{\varepsilon}$-DAGs transform copy-on-write into copy-on-abundant-write

- Gives strong bounds on space amplification
- Preserves locality, even with small writes
- Exploits B$^{\varepsilon}$-tree's batching and flushing

B$^{\varepsilon}$-DAGs preserve the fast reads and writes of B$^{\varepsilon}$-trees

- Preserve logarithmic tree height and query cost
- Preserve asymptotic costs of inserts and updates

Copies are fast and cheap

- GOTO messages enable low-latency DAG mutations
- Total work of copies is O(tree height)

Evaluation Conclusions

BetrFS with B$^\varepsilon$-DAGs has strong copy performance in practice

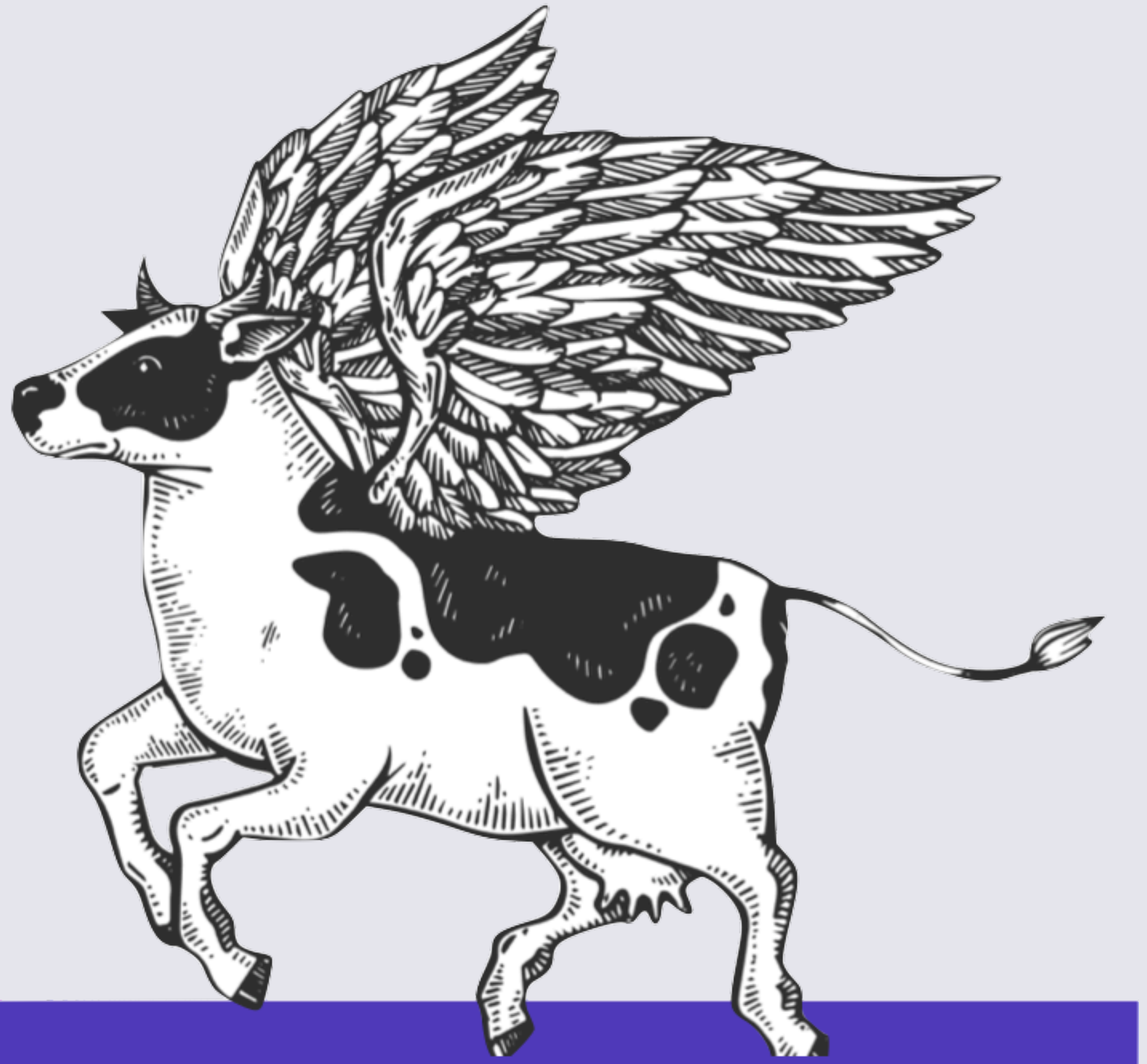
- Low space amplification
- Low latency copying
- Good locality

B$^\varepsilon$-DAGs preserve BetrFS's performance gains on other operations

- Fast random writes
- Good sequential I/O throughput
- No aging
- Strong across-the-board application benchmark performance

Thank you!

The CAW Awakens



BεtrFS Episode V: Attack of the Clones

O'Really? *betrfs.org*