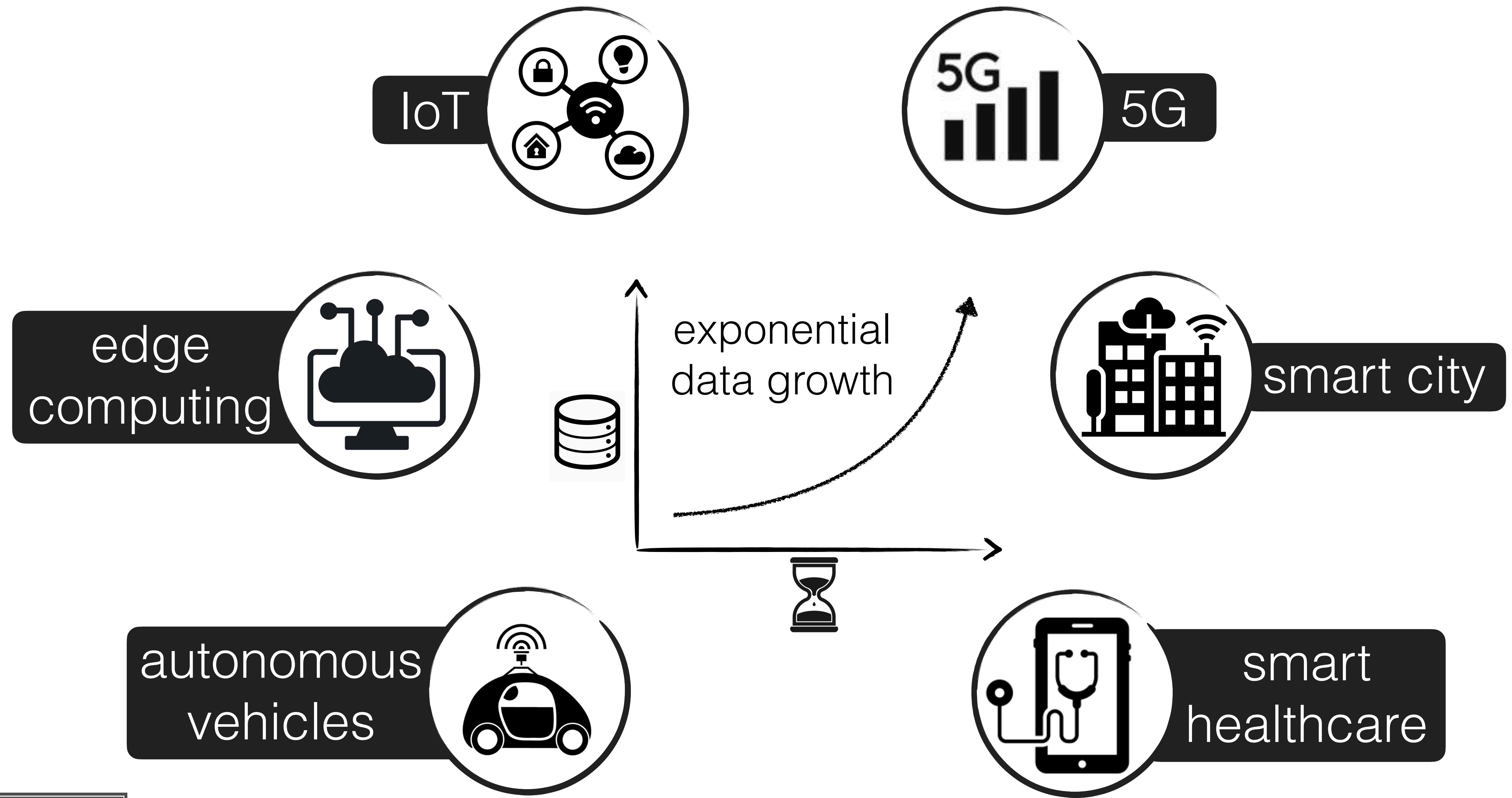
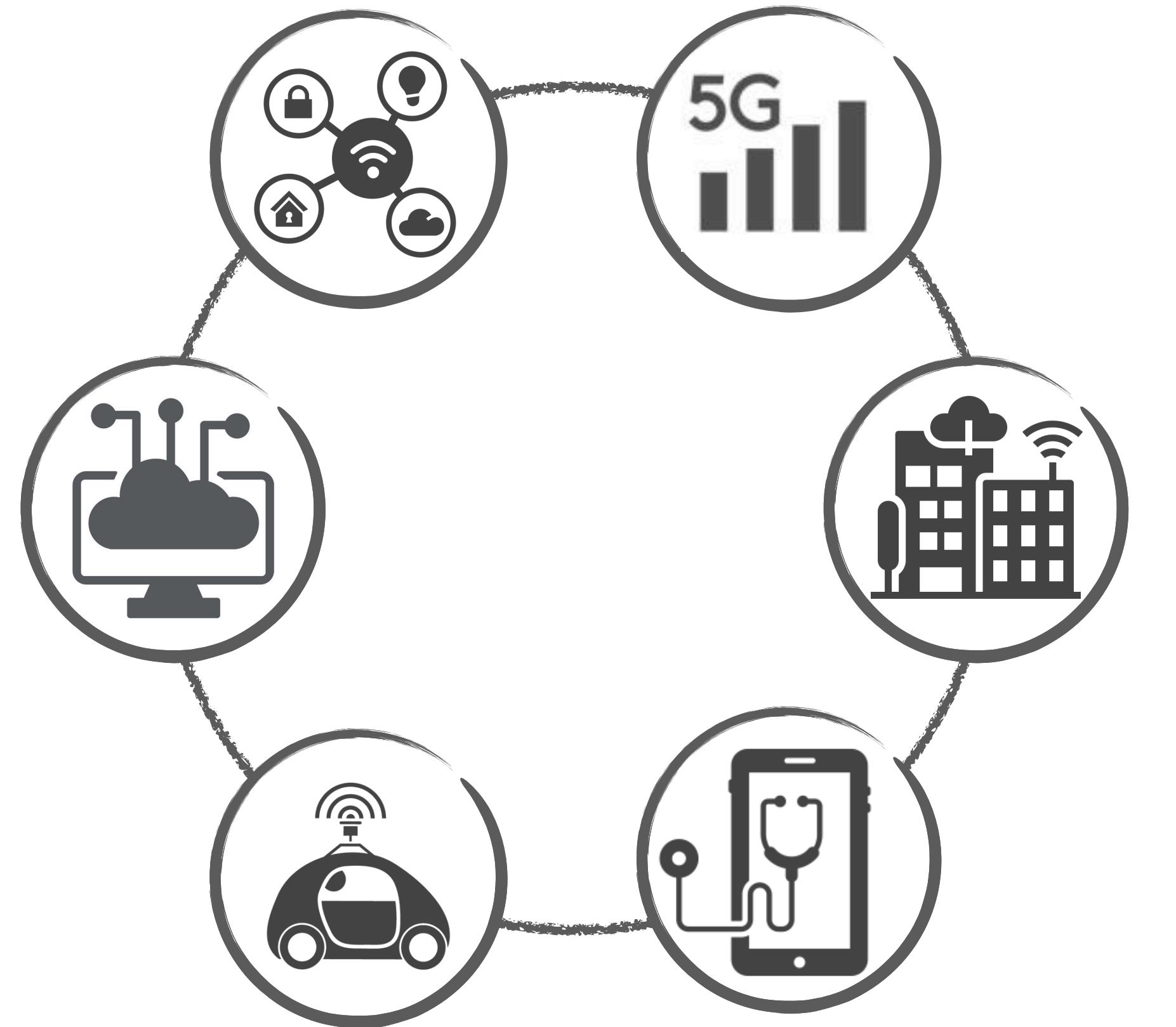




# *Toward Building **Deletion Compliant** Data Systems*

*Subhadeep Sarkar*





fast writes

fast reads

# Out-of-place paradigm

Relational & Array-based



[tile] DB



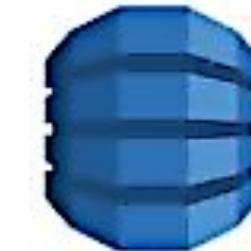
VERTICA



SAP HANA



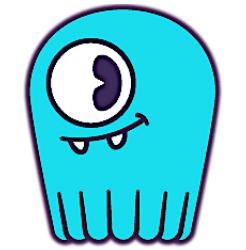
Bigtable



DynamoDB



QuasarDB



SCYLLA



levelDB



: riak



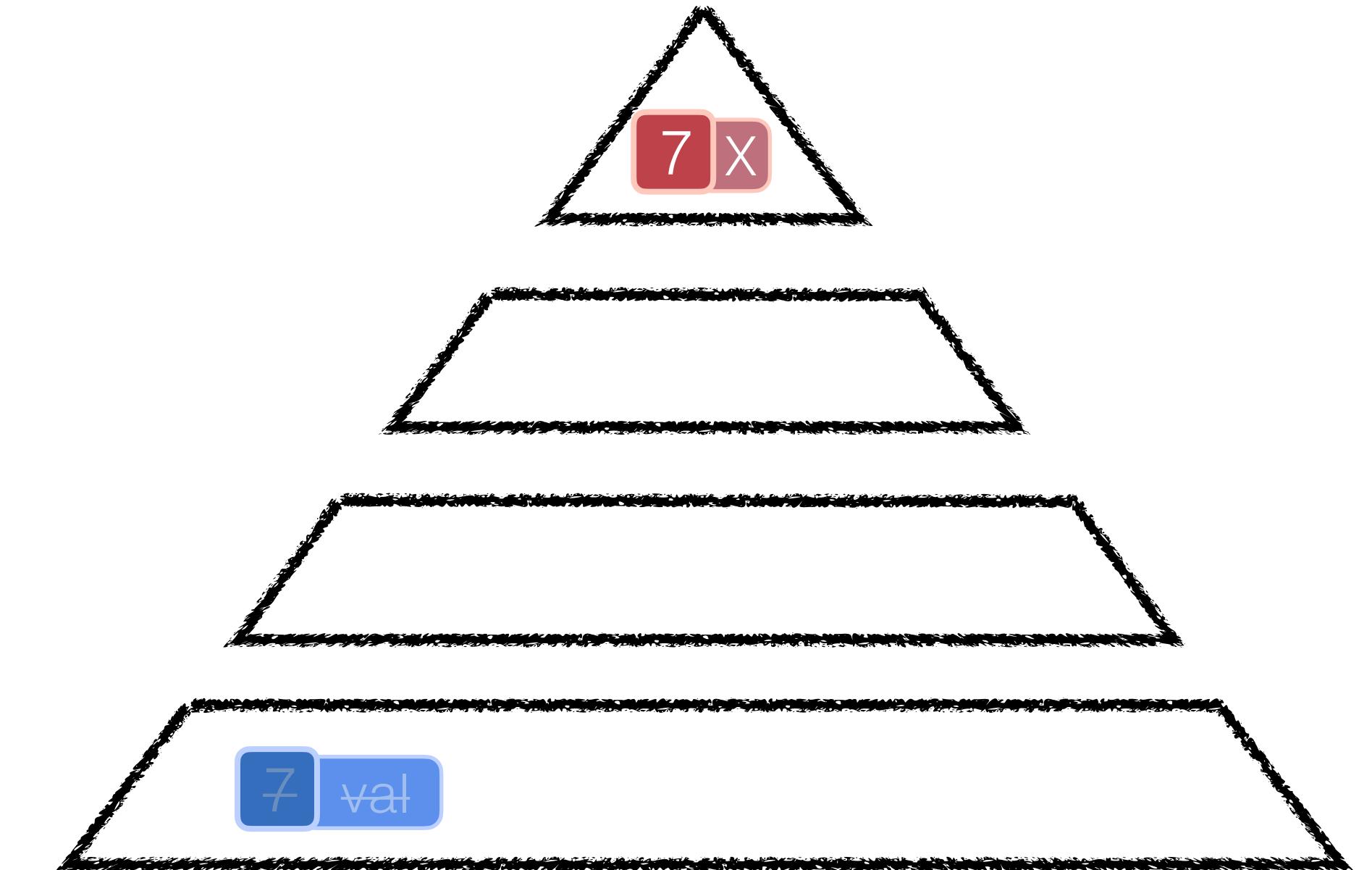
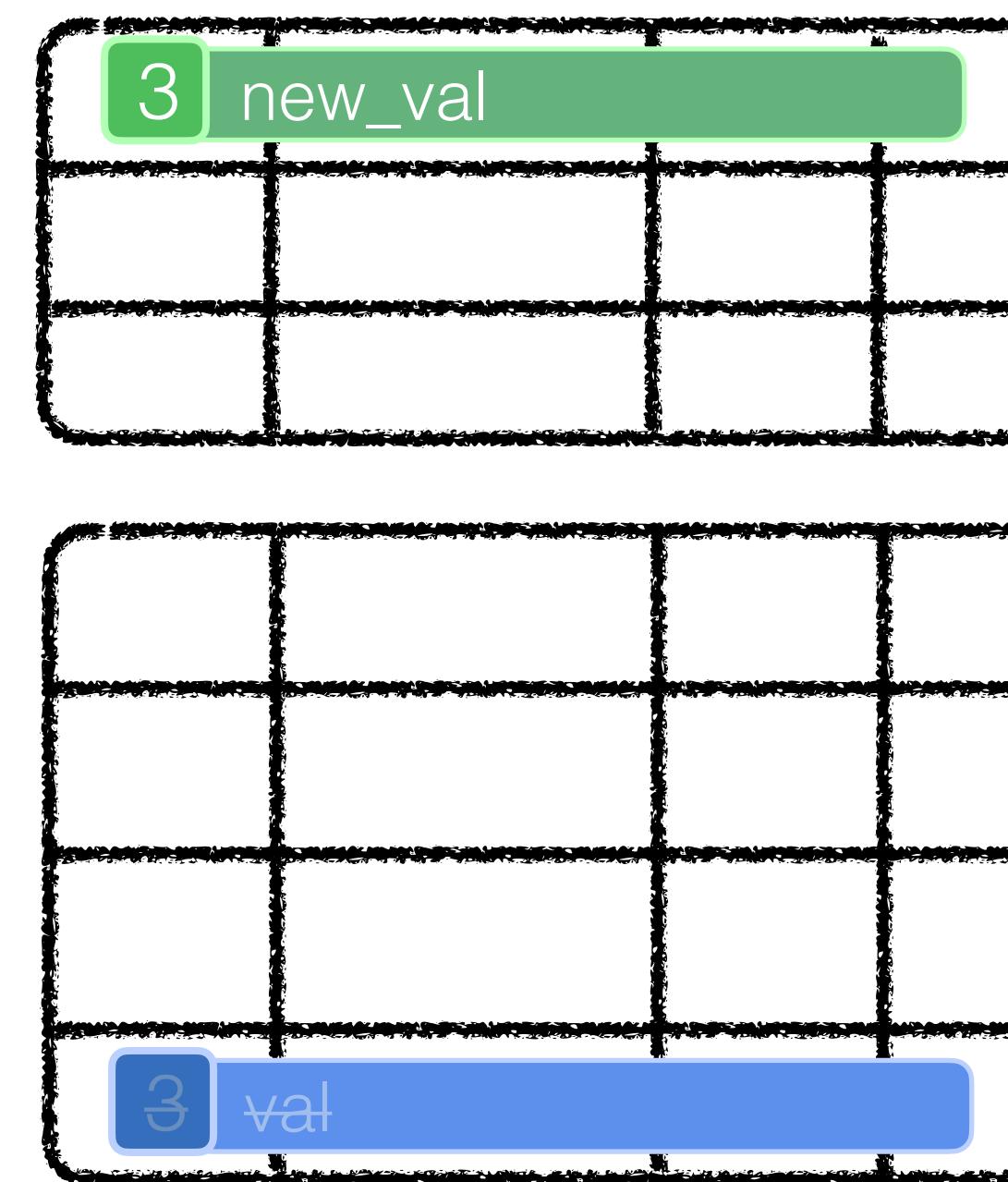
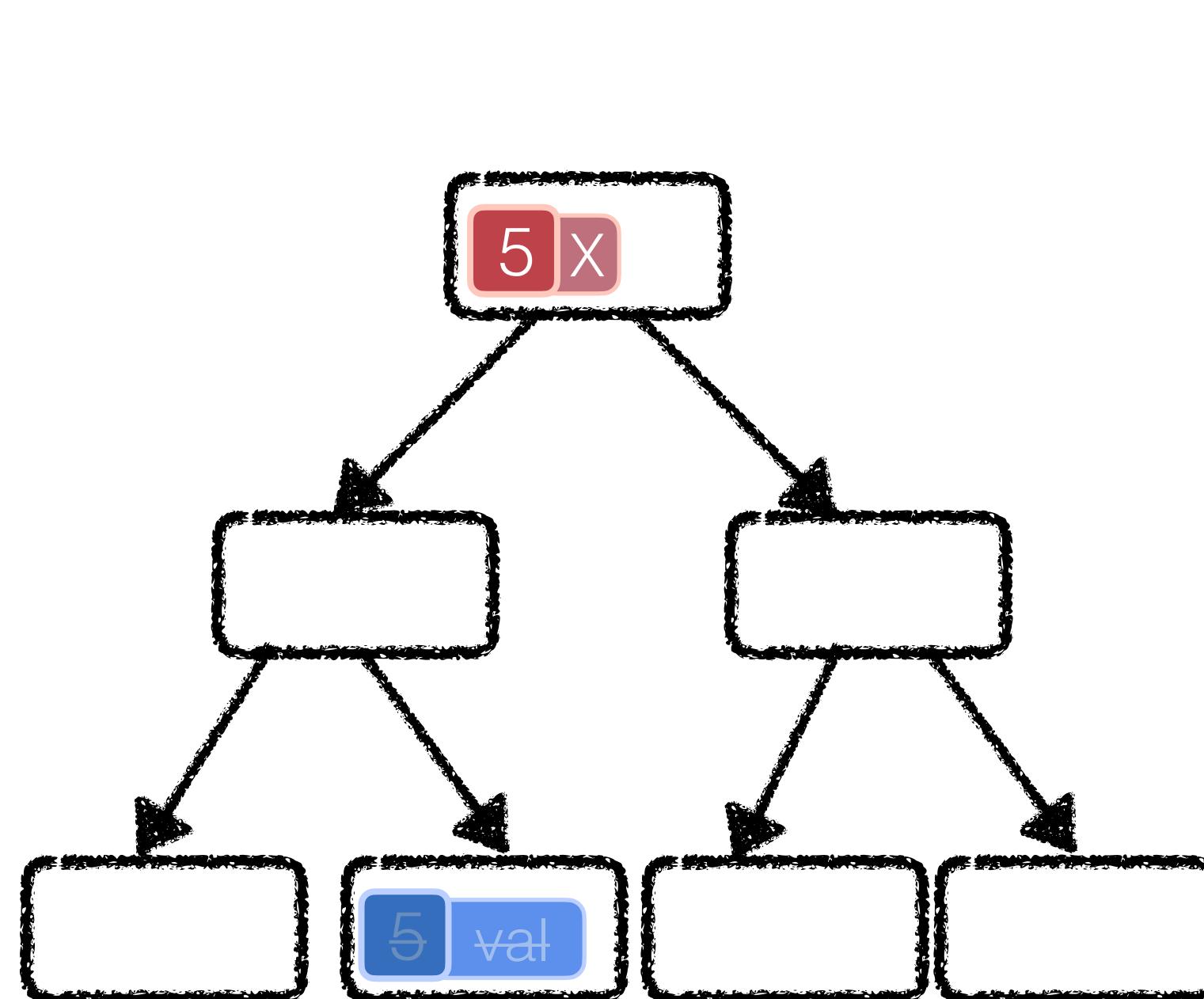
# Out-of-place paradigm

↓

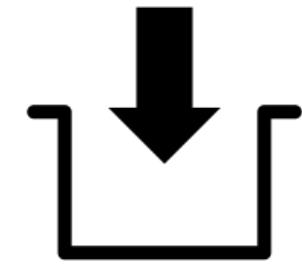
Out-of-place updates/deletes



Merge updates/deletes lazily



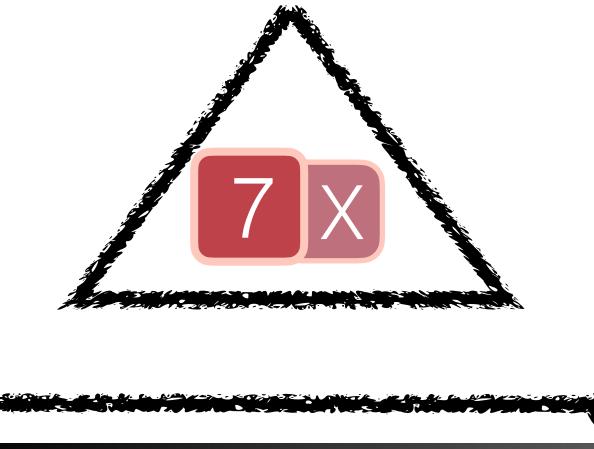
# Out-of-place paradigm



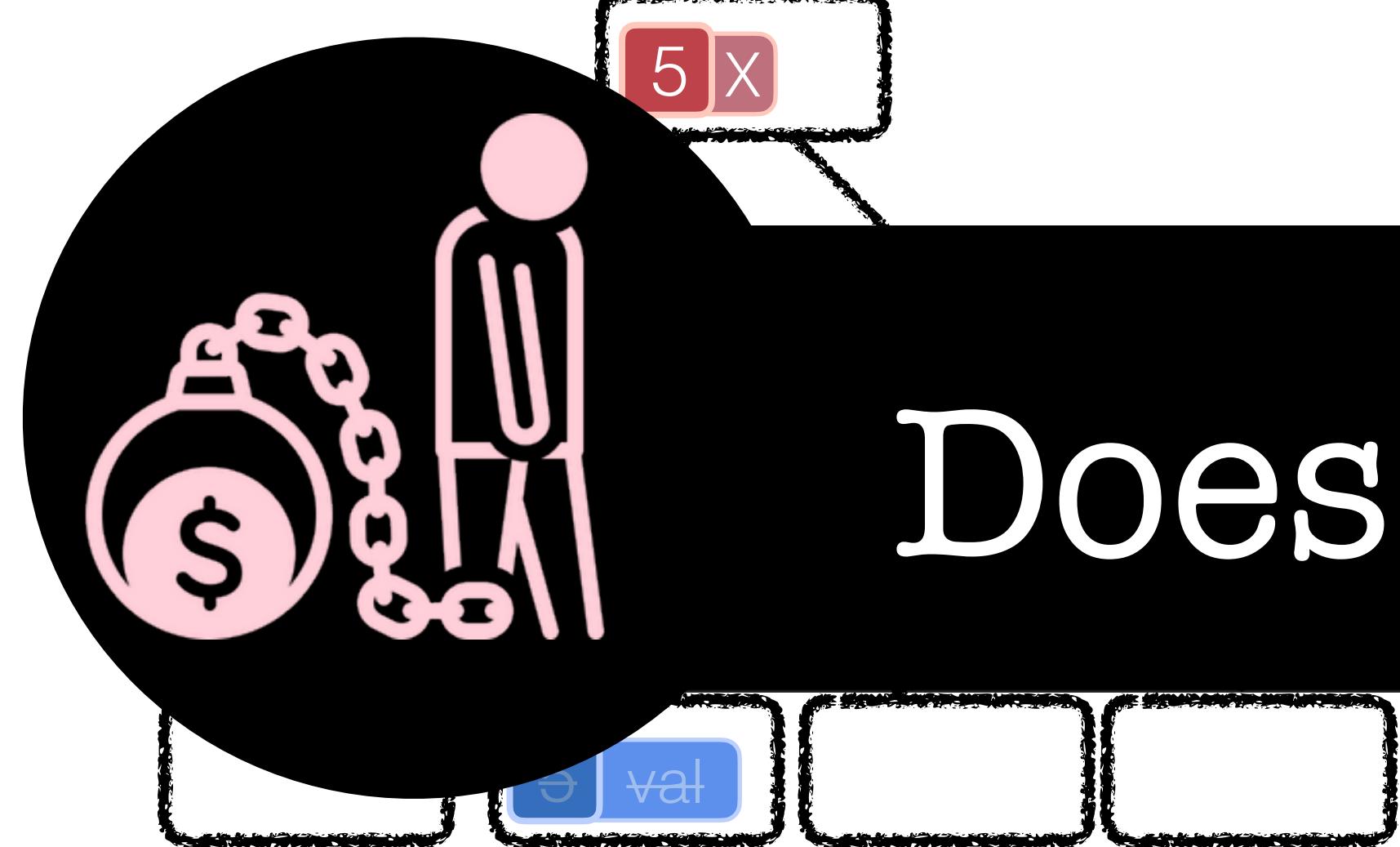
Out-of-place updates/deletes



Merge updates/deletes lazily



Does Not Scale with Deletes!



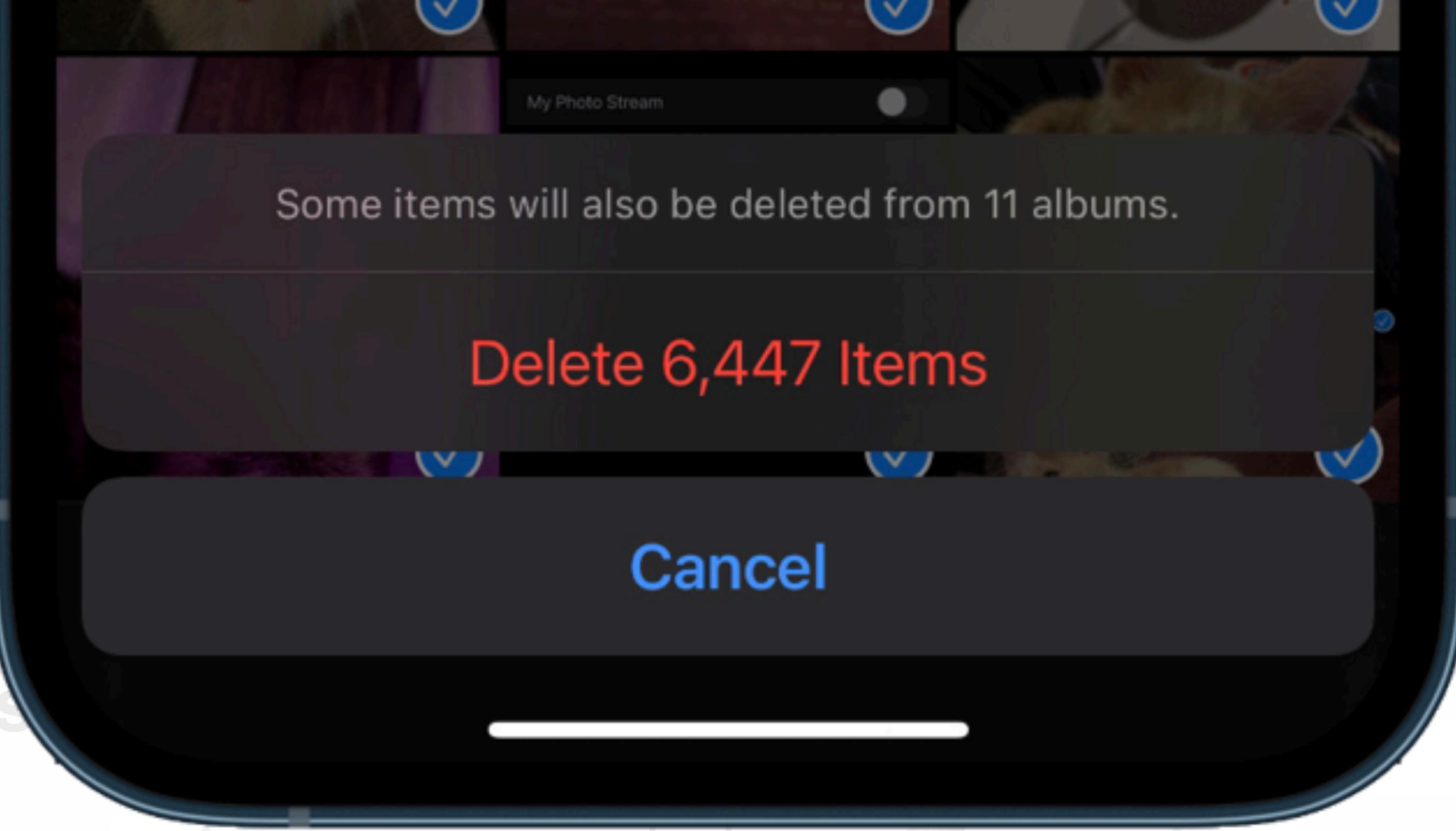
Large-scale  
production

ZippyDB

25.2M deletes  
day

UP2X

100M merge via  
deletes / day



data  
migration

periodic  
cleanup

Privacy  
GDPR  
(EU, UK)

CCPA  
(California)

VCDPA  
(Virginia)

# Large-scale production

ZippyDB 

**25.2M deletes / day**

UP2X 

**100M merge via deletes / day**

# Internal DB ops

table drop 

data migration 

periodic cleanup 

# Privacy

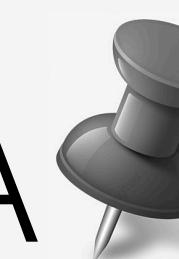


GDPR  
(EU, UK) 



CCPA  
(California) 



VCDPA  
(Virginia) 



GDPR  
(EU, UK)

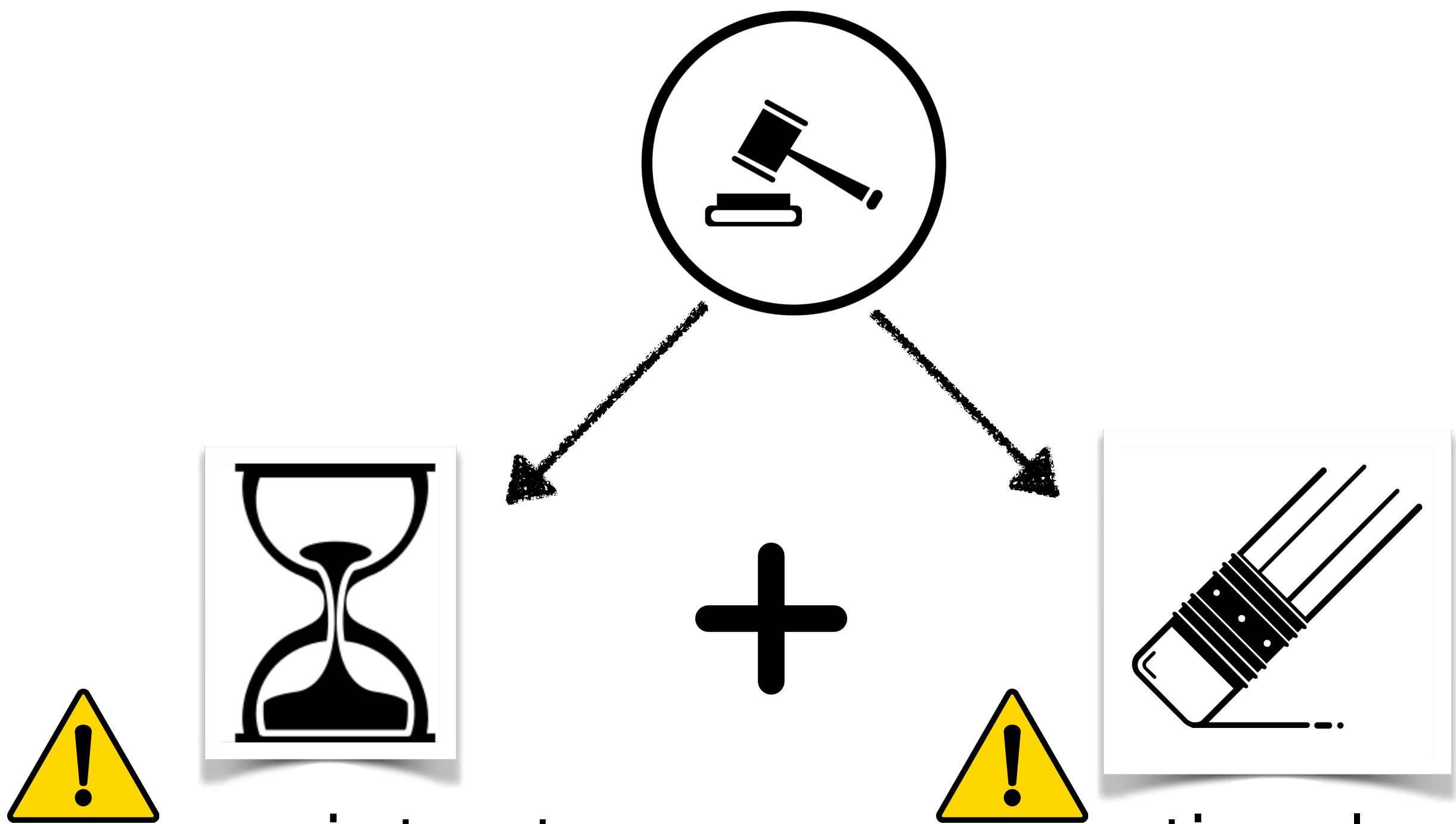


CCPA  
(California)



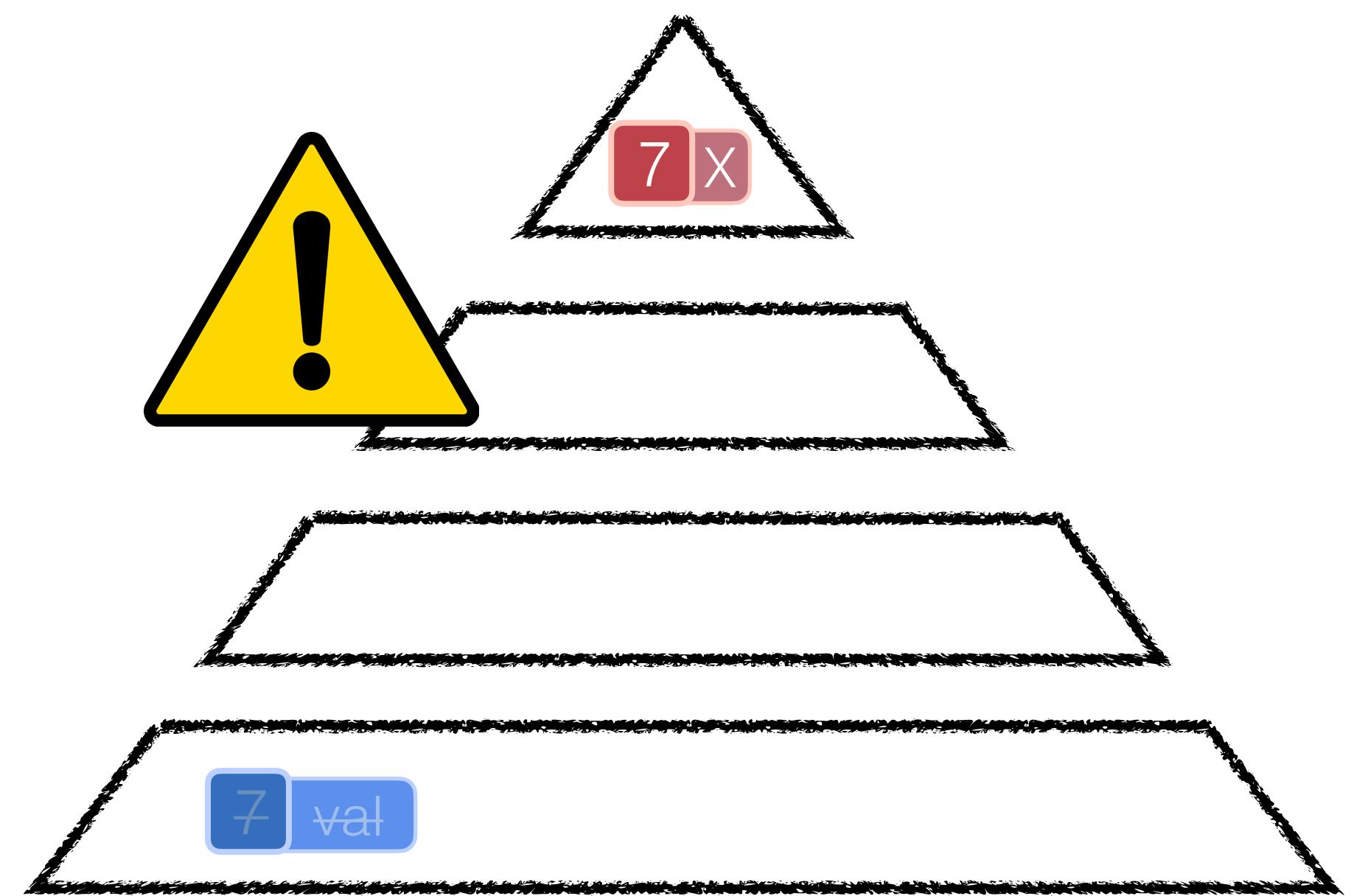
VCPDA  
(Virginia)

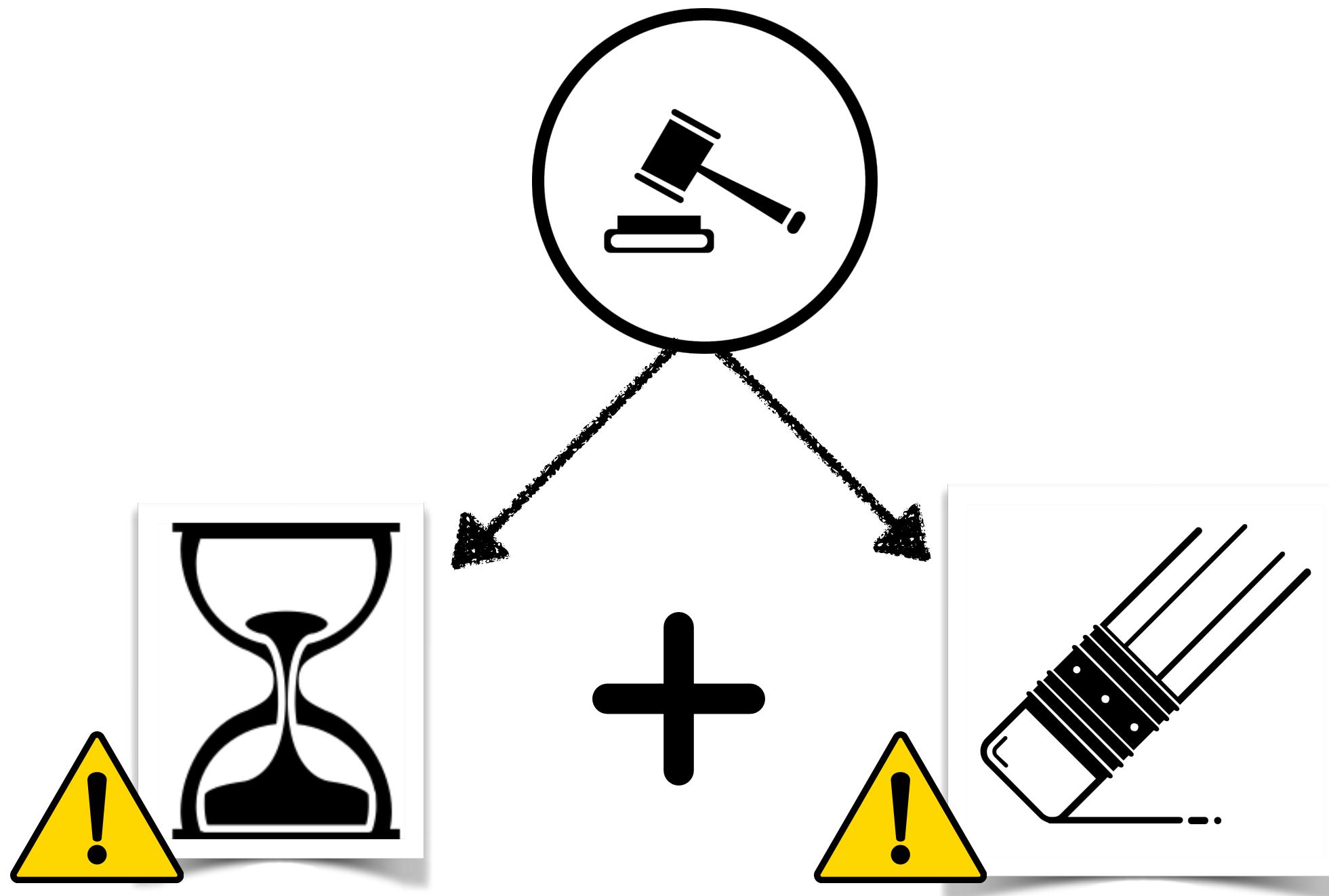
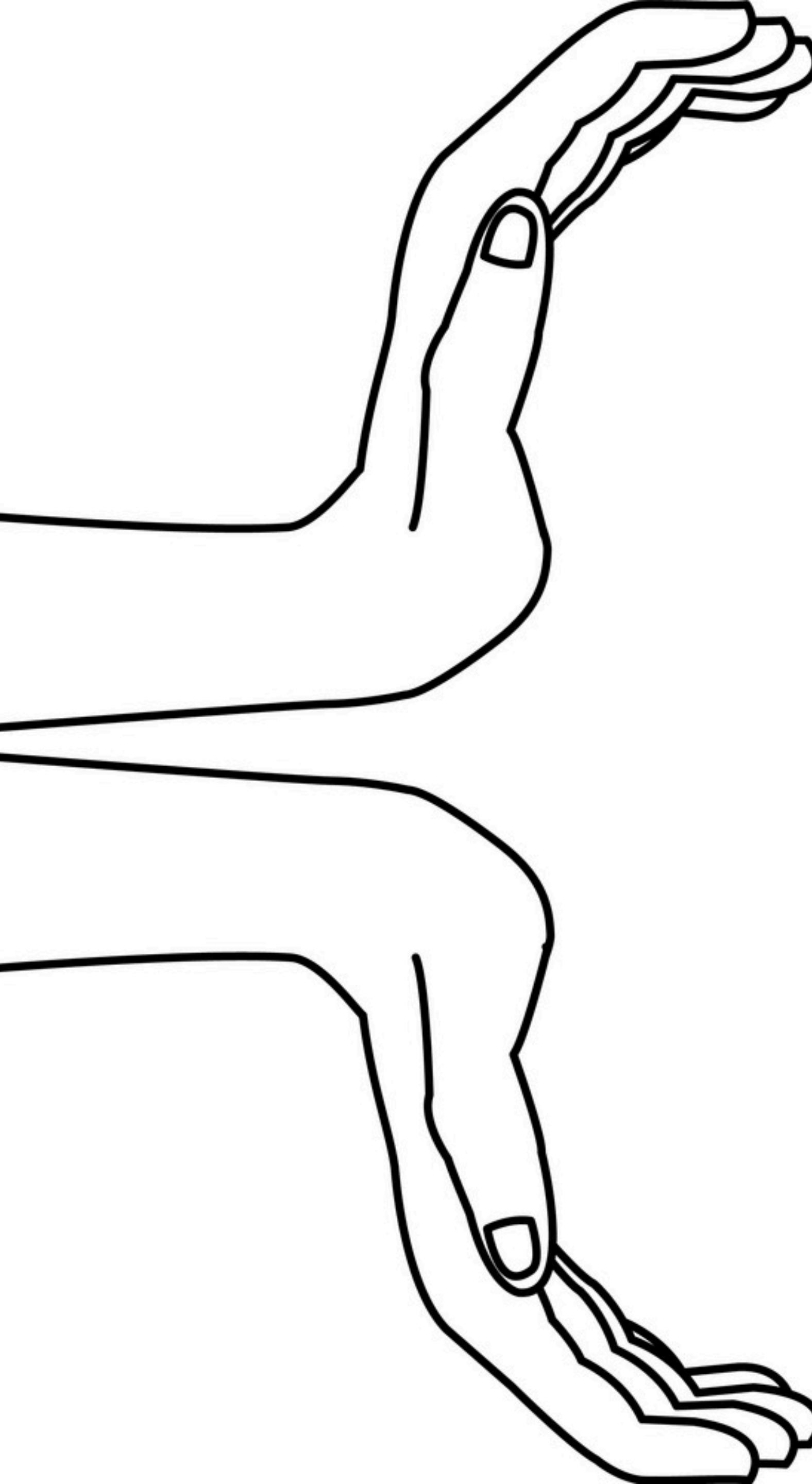
## MANDATES



! persistent  
deletes

! timely  
deletes





persistent  
deletes

timely  
deletes



PRIVACY

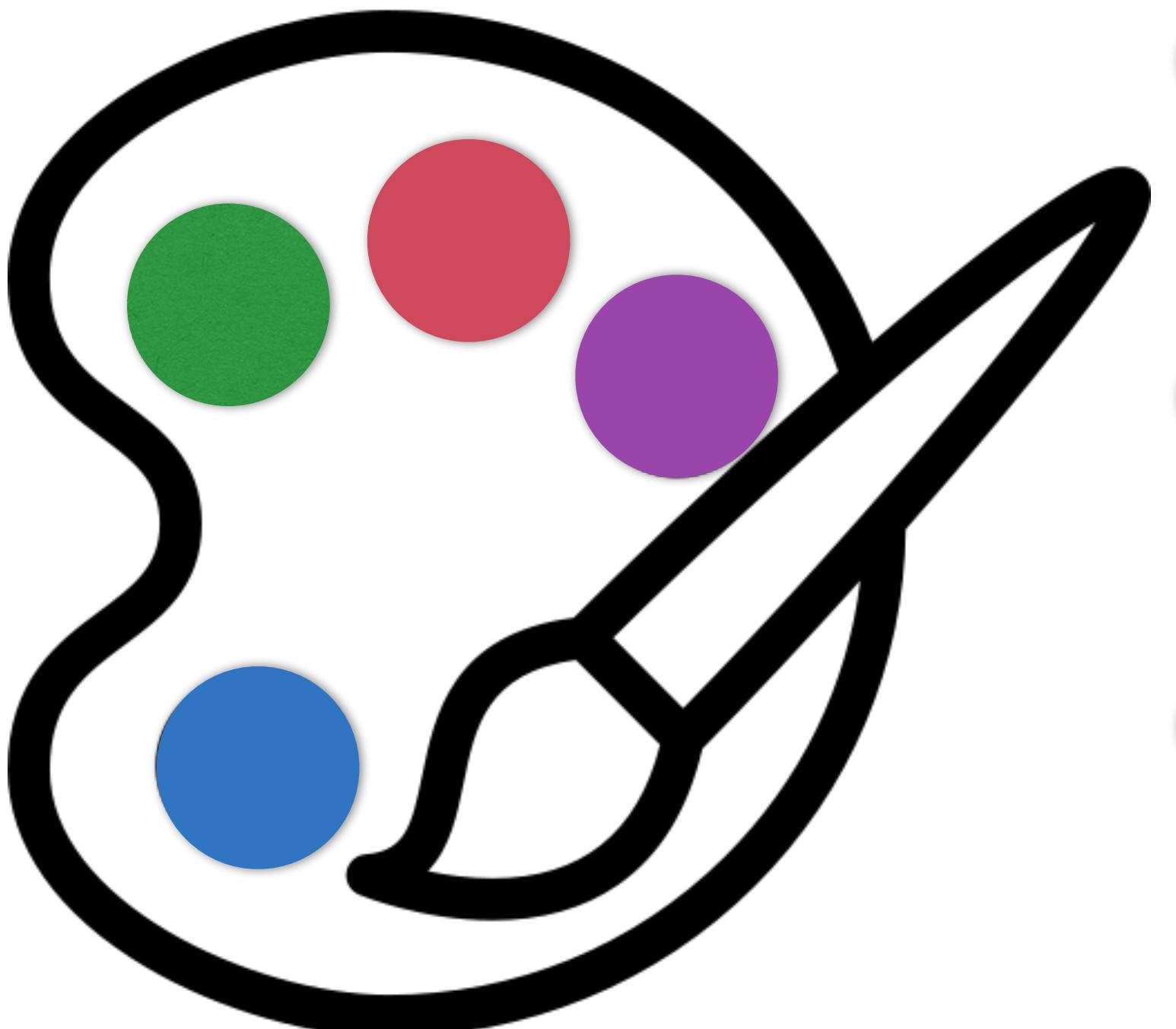
PERFORMANCE



COST

# Our Vision

## PRIVACY-THROUGH-DELETION



- Navigate deletion requirements
- Translate the requirements
- Realize efficient deletes
- Scale with data

# *Regulations*

-  ***Right to be forgotten***
-  ***Right to delete***
-  ***Deletion right***

# Regulations

# Extracting Requirements



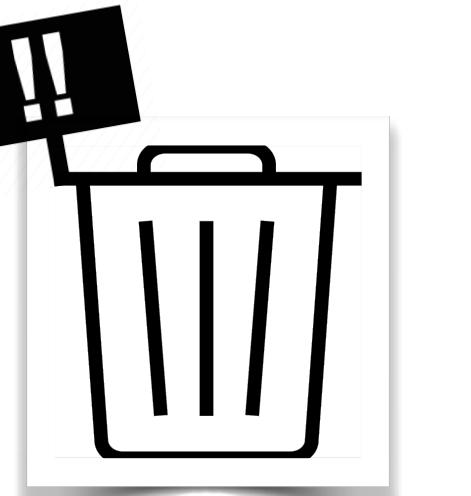
*Right to be forgotten*



*Right to delete*



*Deletion right*



on-demand

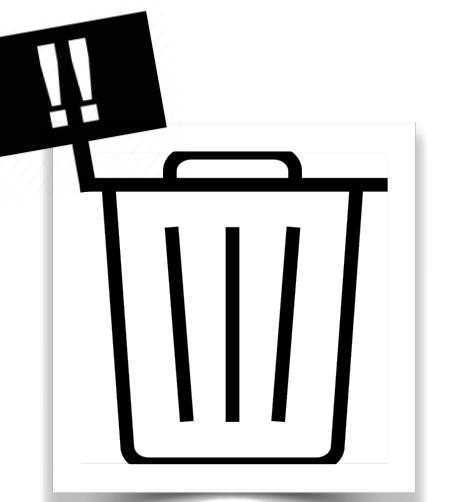
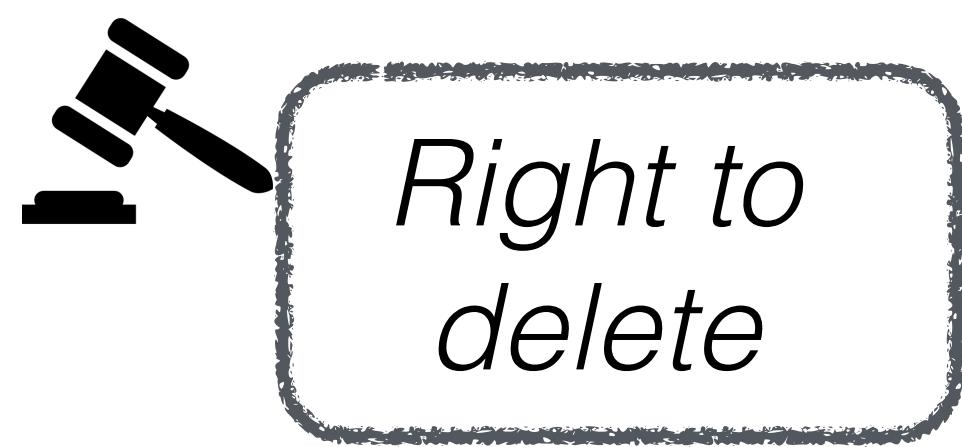


retention-based

# Regulations

# Extracting Requirements

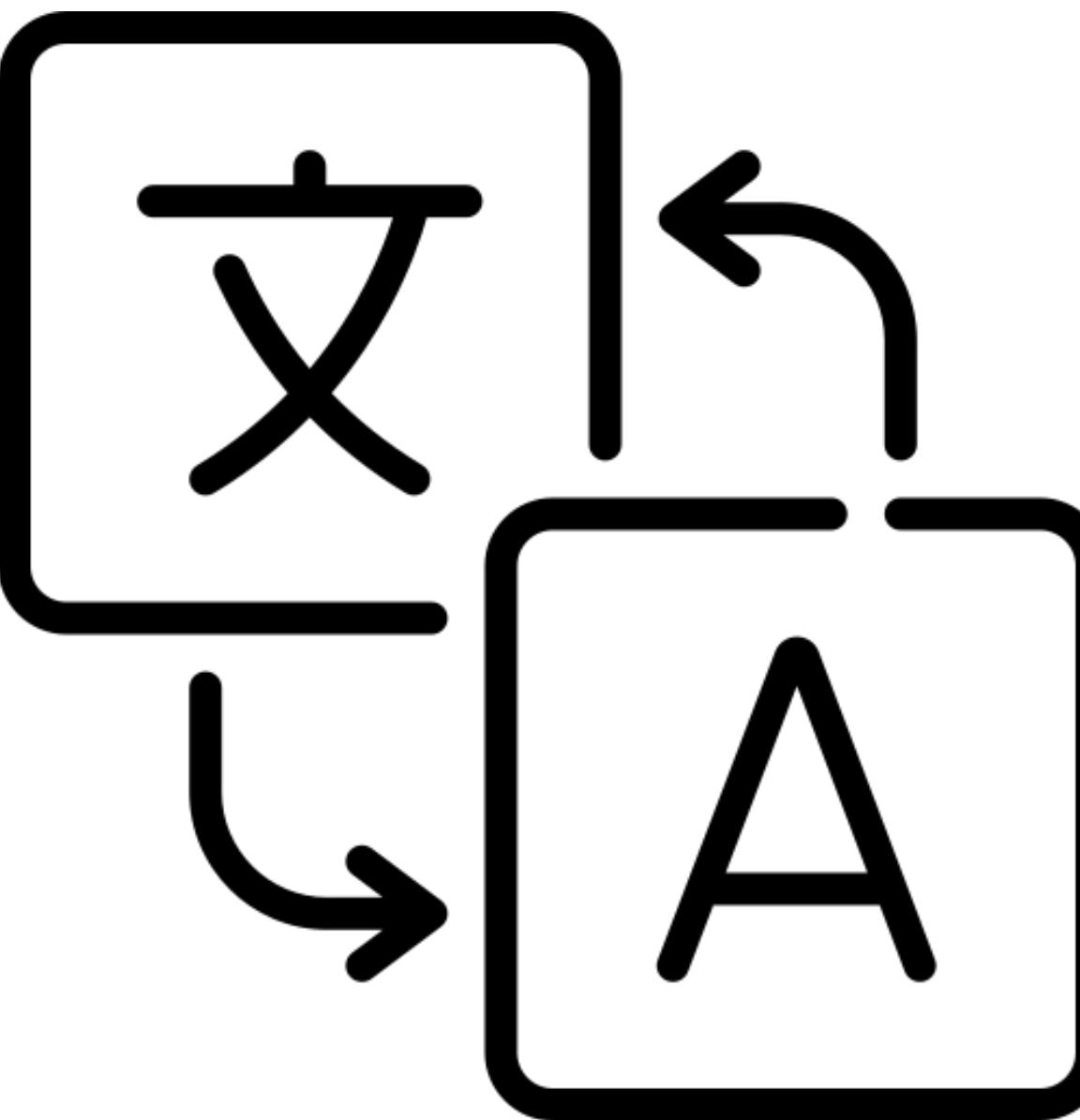
# Query Language Support



on-demand



retention-based



requirement  
translation

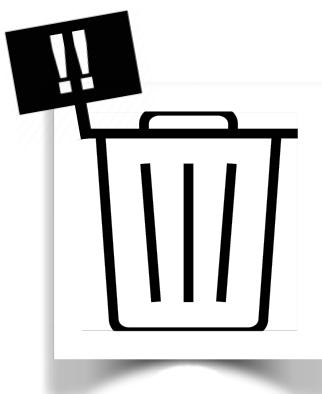
# SQL-support for deletes

CREATE TABLE R (column1 type1, column2 type2, ...)



WITH RET\_DUR

{ARBITRARY|FIXED (t1 <ret1>, t1 <ret1>, ...)}



WITH DPT

{ARBITRARY|FIXED (d1 <dpt1>, d1 <dpt1>, ...)};

INSERT INTO R (val1, val2, ...)

WITH RET\_DUR {<t>|t<i>};

DELETE FROM R

WHERE (...)

WITH DPT {<d>|d<i>};

# Regulations

# Extracting Requirements

# Query Language Support



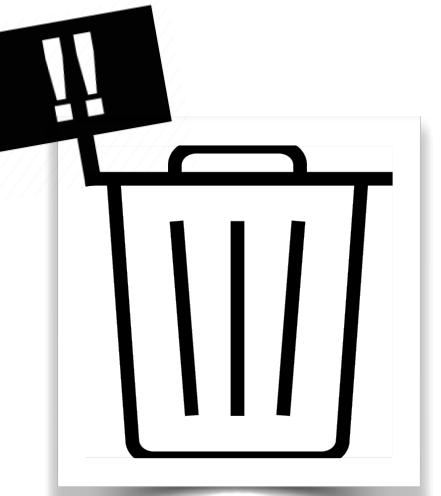
*Right to be forgotten*



*Right to delete*



*Deletion right*



on-demand



retention-based

```
CREATE TABLE R (...)  
WITH RET_DUR  
{ARBITRARY | FIXED(...)}  
WITH DPT  
{ARBITRARY | FIXED(...)};
```

```
INSERT INTO R (...)  
WITH RET_DUR {<t>|t<i>};
```

```
DELETE FROM R  
WHERE (...)  
WITH DPT {<d>|d<i>};
```

# Regulations



*Right to be forgotten*



*Right to delete*



*Deletion right*

# Extracting Requirements



on-demand



retention-based

# Query Language Support

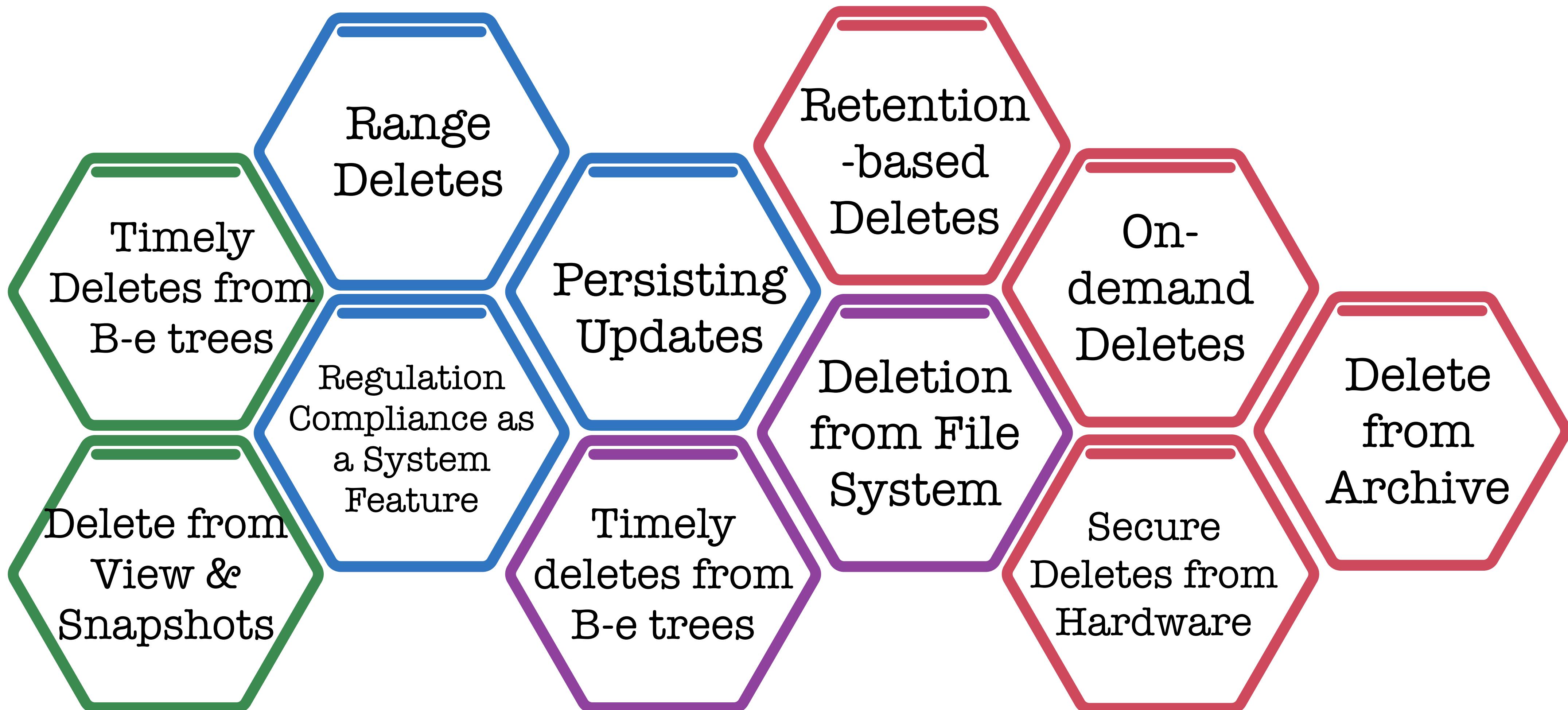
```
CREATE TABLE R (...)  
WITH RET_DUR  
{ARBITRARY | FIXED(...)}  
WITH DPT  
{ARBITRARY | FIXED(...)};
```

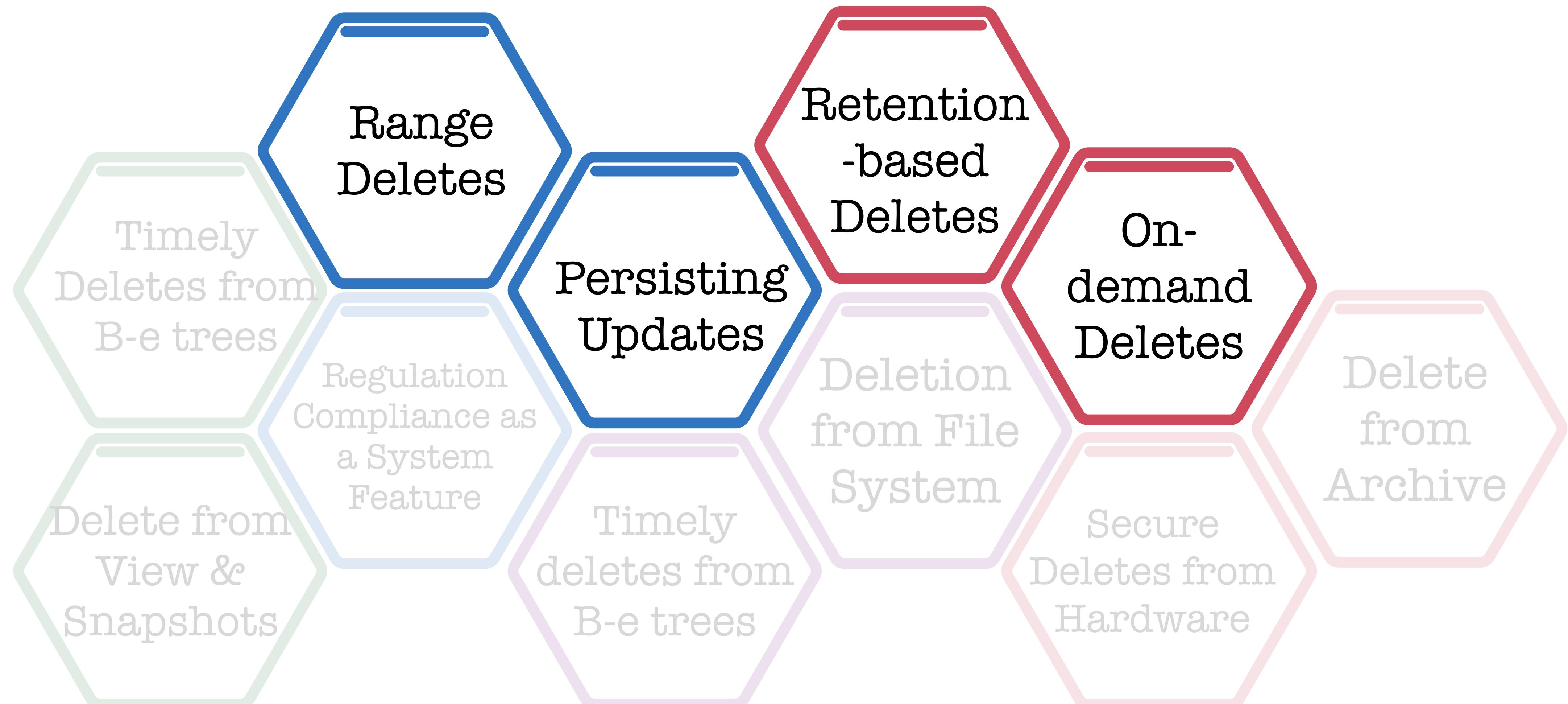
```
INSERT INTO R (...)  
WITH RET_DUR {<t>|t<i>};
```

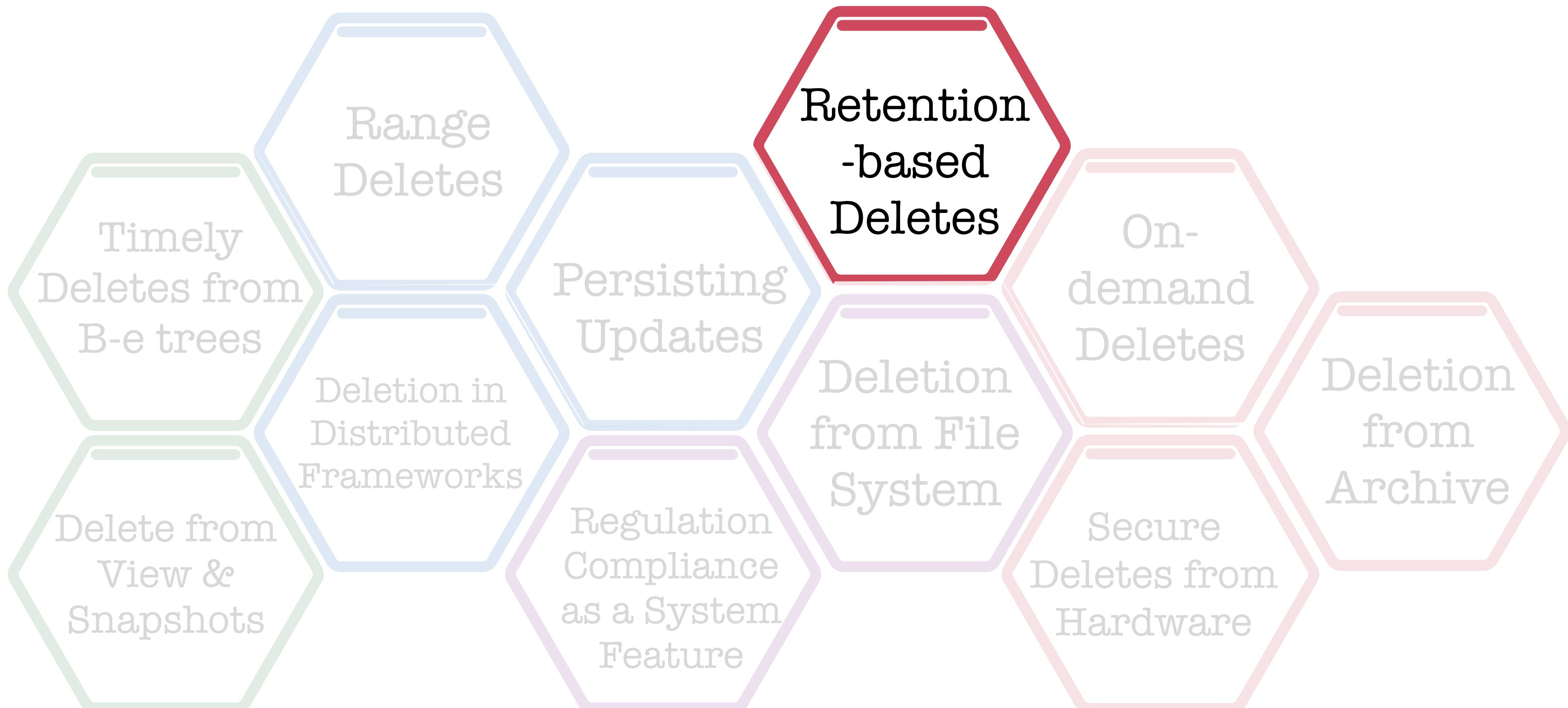
```
DELETE FROM R  
WHERE (...)  
WITH DPT {<d>|d<i>};
```

# System Support

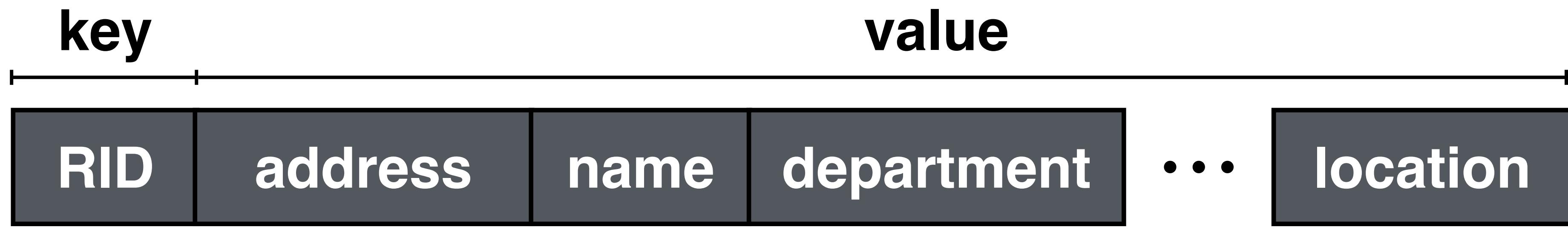


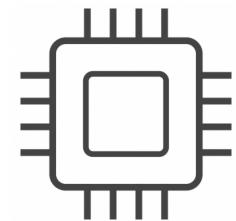






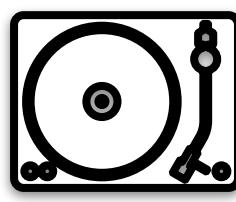
# Log-Structured Merge-tree

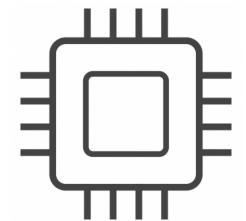




buffer

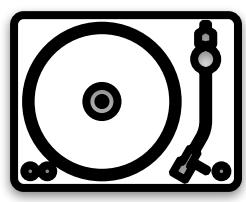
|   |   |   |   |
|---|---|---|---|
| 2 | 6 | 1 | 4 |
|---|---|---|---|

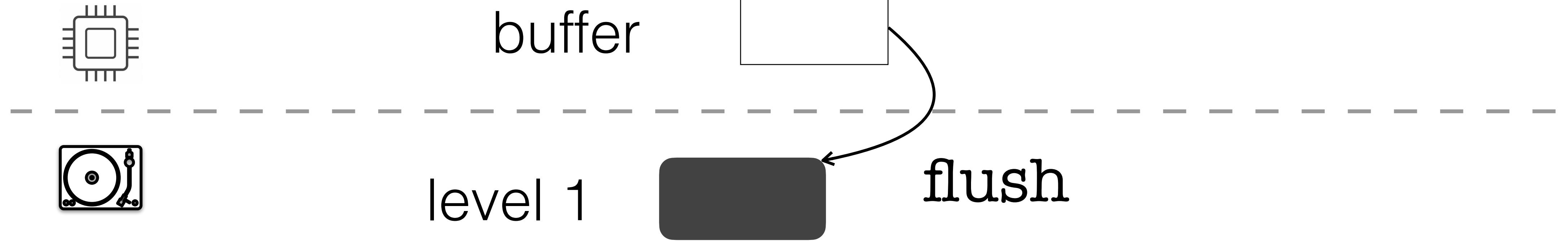


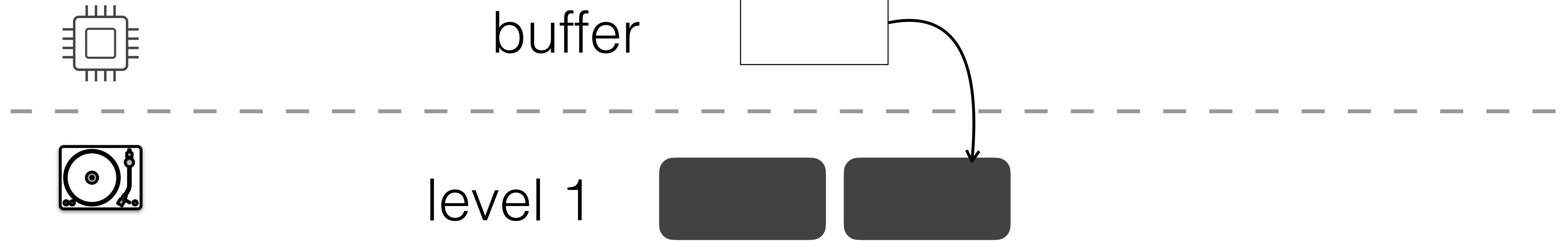


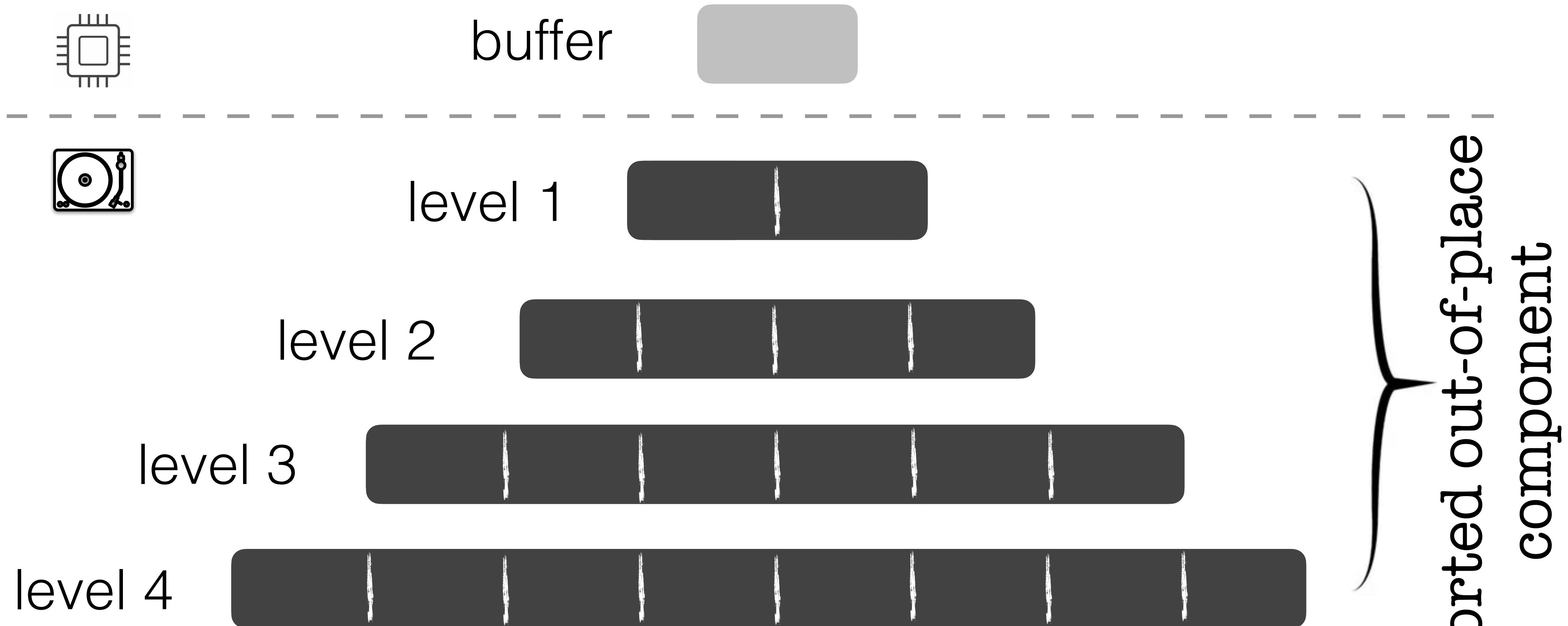
buffer

|   |   |   |   |
|---|---|---|---|
| 1 | 2 | 4 | 6 |
|---|---|---|---|



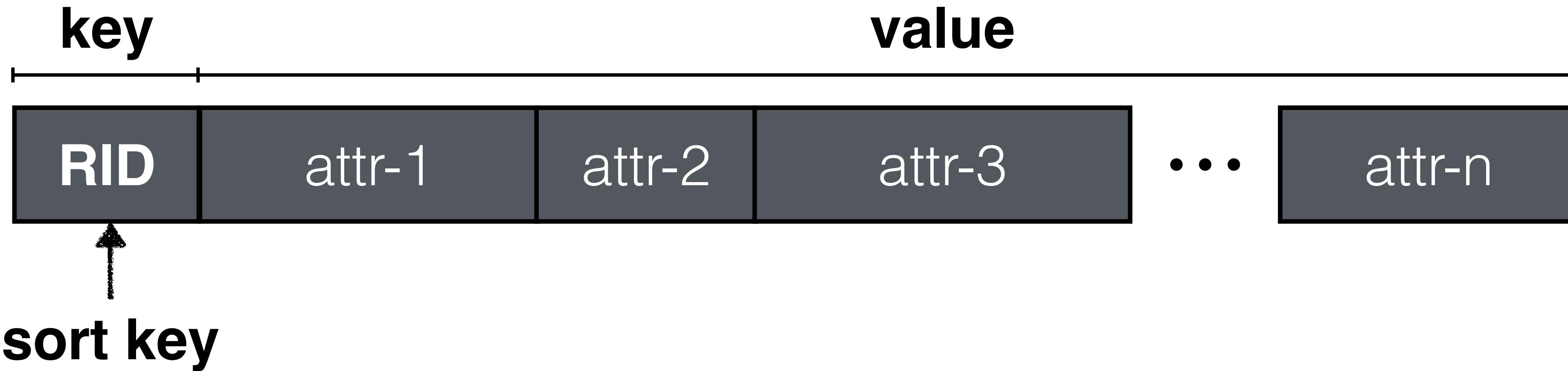






# Realizing Retention-Based Deletes

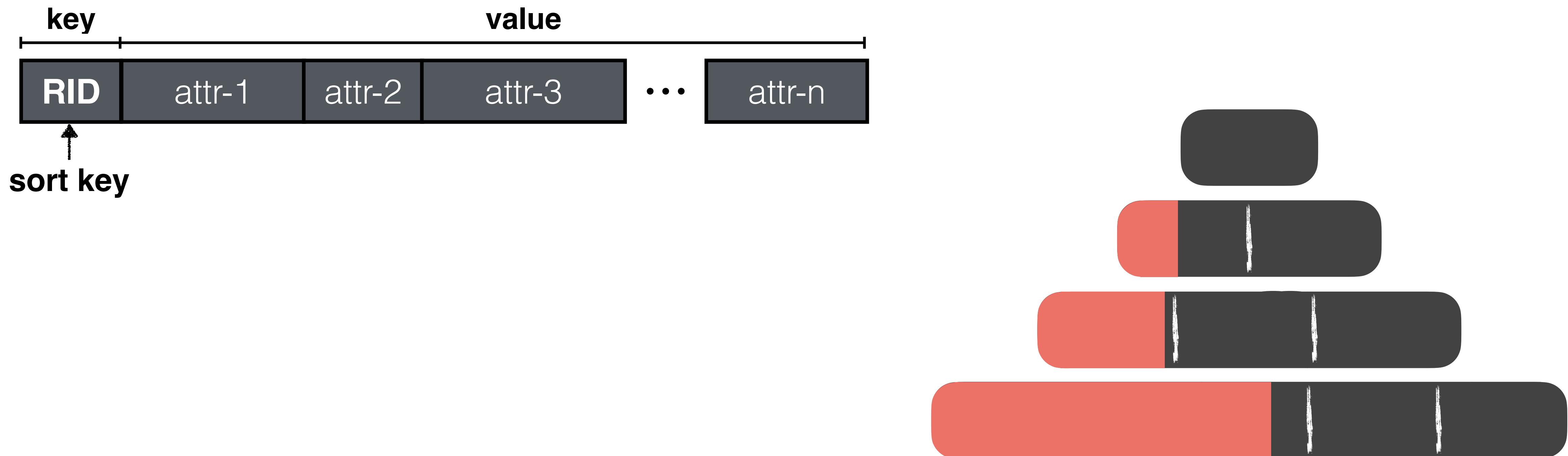
delete all entries older than:  $TS_x$



sort key = delete key

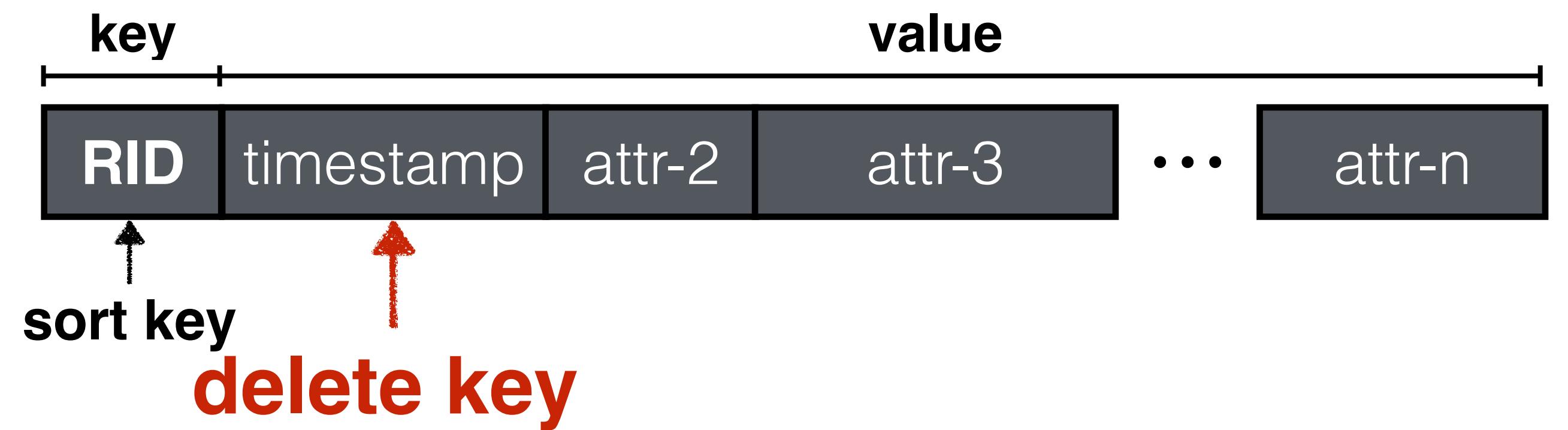
# Realizing Retention-Based Deletes

delete all entries older than:  $TS_x$

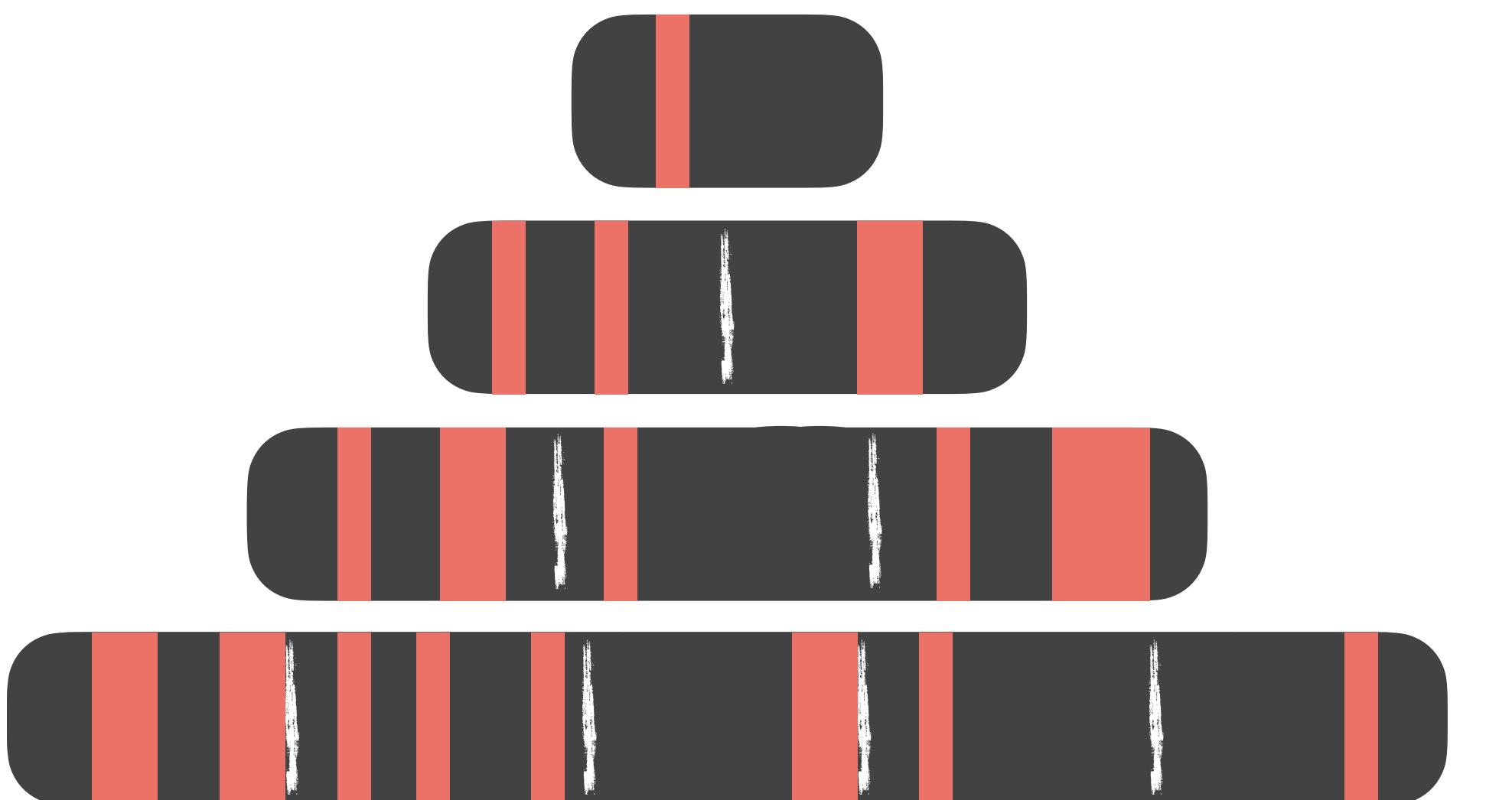


# Realizing Retention-Based Deletes

delete all entries older than:  $TS_x$



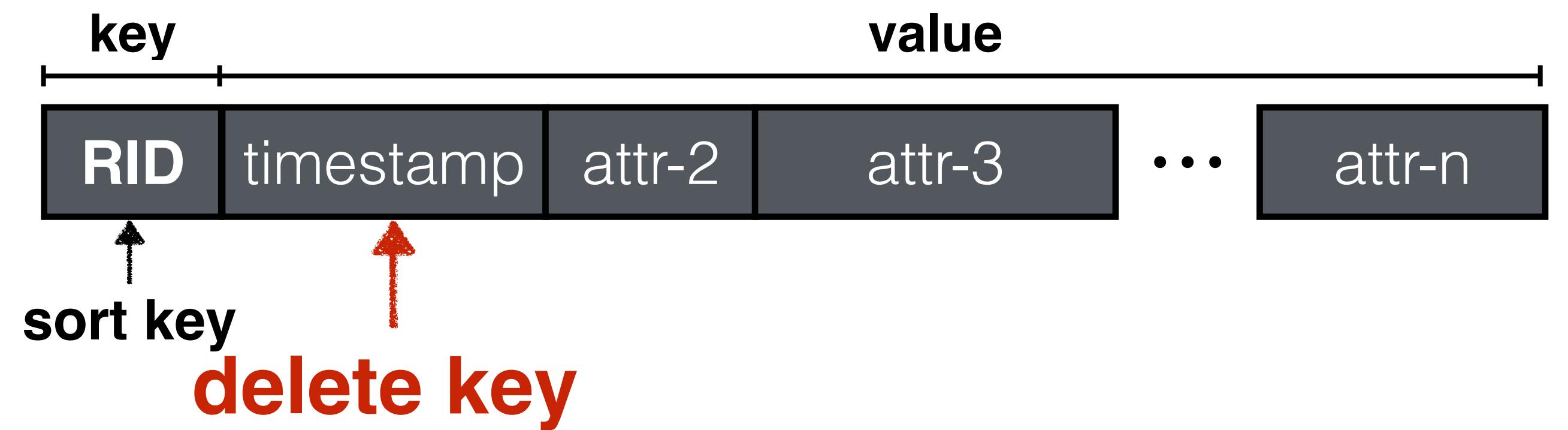
sort key ≠ delete key



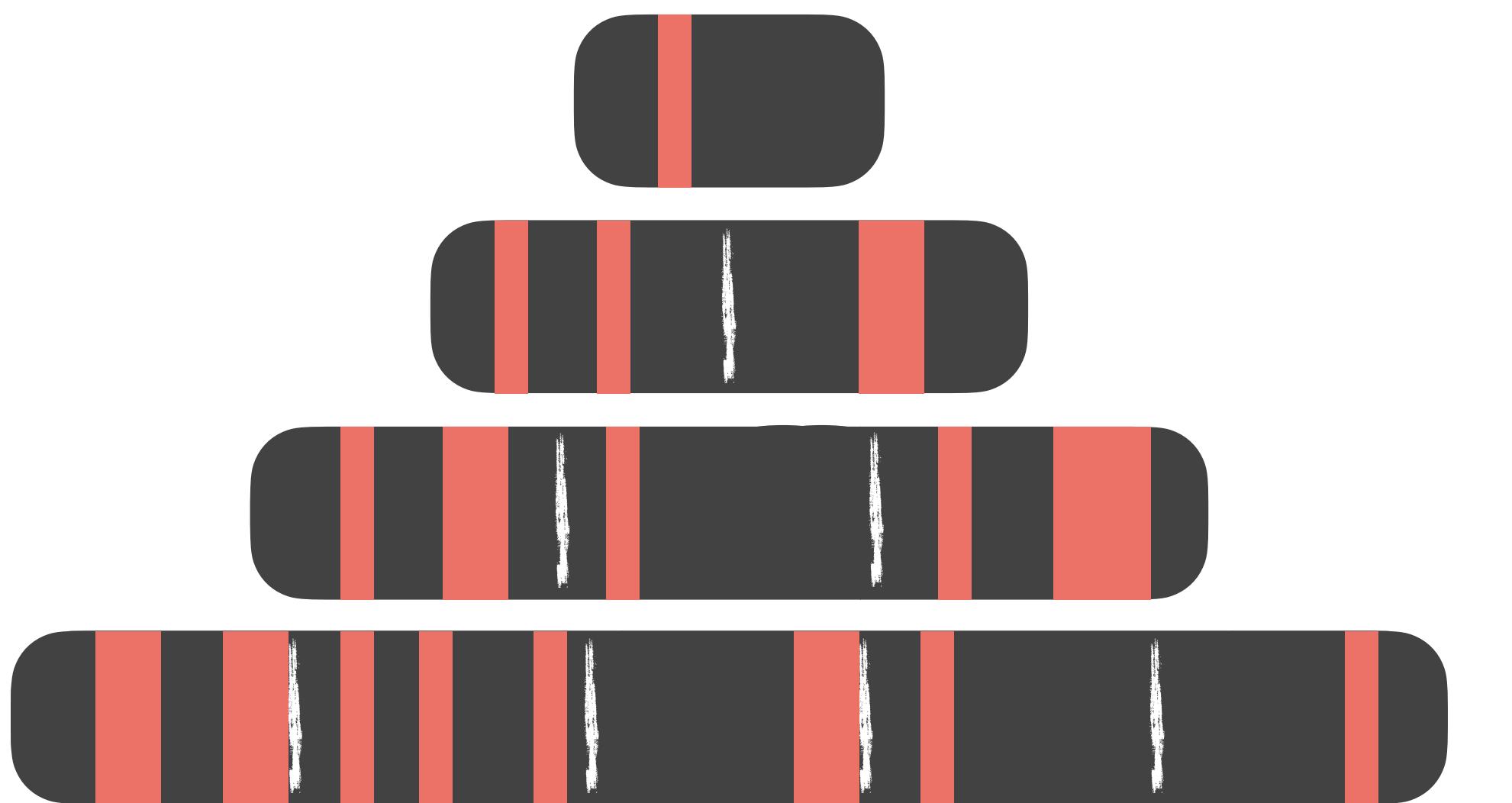
# scattered occurrences

# Realizing Retention-Based Deletes

delete all entries older than:  $TS_x$



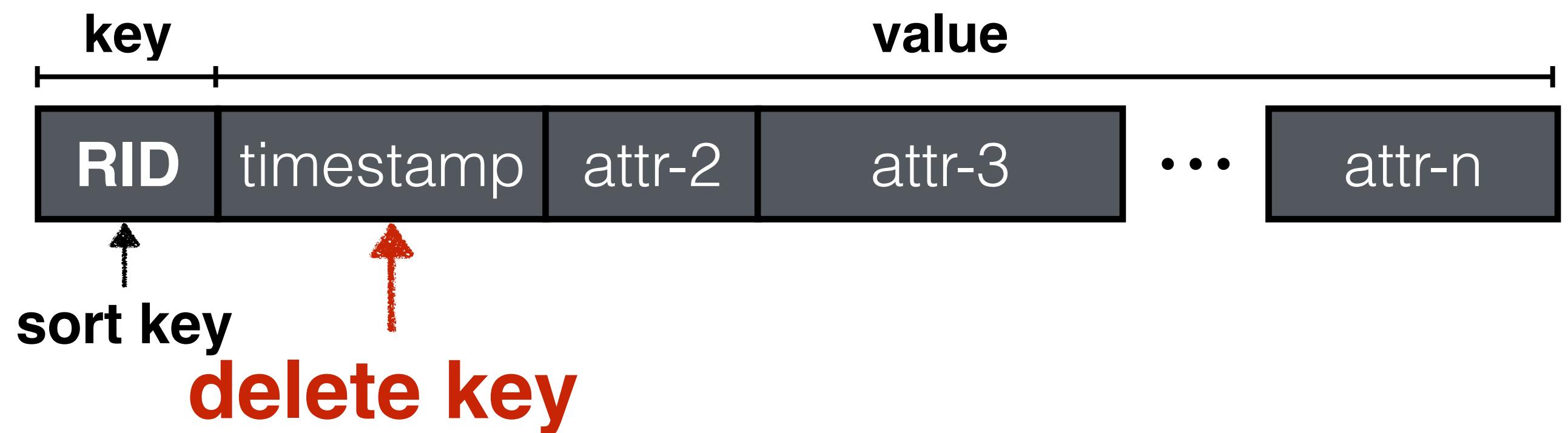
sort key ≠ delete key



# scattered occurrences

# Realizing Retention-Based Deletes

delete all entries older than:  $TS_x$



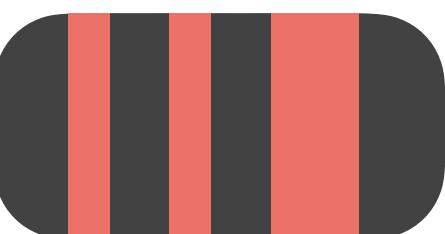
sort key  $\neq$  delete key

- latency spikes X
- superfluous I/Os X



# Realizing Retention-Based Deletes

delete all entries older than  $\leq 65_D$



SST file

|                               |                               |
|-------------------------------|-------------------------------|
| $S_{min}=1 :: S_{max}=99$     |                               |
| $D_{min}=1_D :: D_{max}=90_D$ |                               |
| page 1                        | $S_{min}=1 :: S_{max}=24$     |
|                               | $D_{min}=3_D :: D_{max}=80_D$ |
| page 2                        | $S_{min}=29 :: S_{max}=60$    |
|                               | $D_{min}=9_D :: D_{max}=90_D$ |
| page 3                        | $S_{min}=61 :: S_{max}=79$    |
|                               | $D_{min}=1_D :: D_{max}=89_D$ |
| page 4                        | $S_{min}=80 :: S_{max}=99$    |
|                               | $D_{min}=7_D :: D_{max}=85_D$ |
|                               | ⋮                             |

| page 1 |      |     |      |     |      |      |      |
|--------|------|-----|------|-----|------|------|------|
| 1      | 4    | 9   | 14   | 15  | 19   | 20   | 24   |
| 34_D   | 69_D | 3_D | 79_D | 8_D | 80_D | 23_D | 24_D |

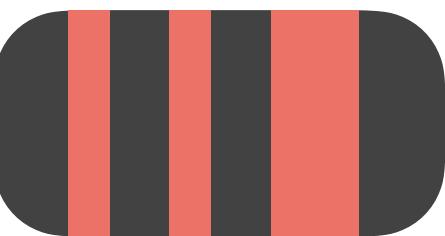
| page 2 |      |      |      |     |      |      |      |
|--------|------|------|------|-----|------|------|------|
| 29     | 32   | 33   | 40   | 44  | 52   | 56   | 60   |
| 88_D   | 90_D | 28_D | 74_D | 9_D | 76_D | 81_D | 64_D |

| page 3 |      |     |      |      |      |      |      |
|--------|------|-----|------|------|------|------|------|
| 61     | 63   | 67  | 71   | 72   | 73   | 78   | 79   |
| 75_D   | 82_D | 1_D | 67_D | 77_D | 89_D | 65_D | 12_D |

| page 4 |      |      |     |      |      |      |      |
|--------|------|------|-----|------|------|------|------|
| 80     | 84   | 86   | 87  | 91   | 94   | 95   | 99   |
| 70_D   | 41_D | 62_D | 7_D | 25_D | 85_D | 59_D | 19_D |

# Realizing Retention-Based Deletes

delete all entries older than  $\leq 65_D$



SST file

|                               |                               |
|-------------------------------|-------------------------------|
| $S_{min}=1 :: S_{max}=99$     |                               |
| $D_{min}=1_D :: D_{max}=90_D$ |                               |
| page 1                        | $S_{min}=1 :: S_{max}=24$     |
|                               | $D_{min}=3_D :: D_{max}=80_D$ |
| page 2                        | $S_{min}=29 :: S_{max}=60$    |
|                               | $D_{min}=9_D :: D_{max}=90_D$ |
| page 3                        | $S_{min}=61 :: S_{max}=79$    |
|                               | $D_{min}=1_D :: D_{max}=89_D$ |
| page 4                        | $S_{min}=80 :: S_{max}=99$    |
|                               | $D_{min}=7_D :: D_{max}=85_D$ |
| $\vdots$                      |                               |

| page 1 |      |     |      |     |      |      |      |
|--------|------|-----|------|-----|------|------|------|
| 1      | 4    | 9   | 14   | 15  | 19   | 20   | 24   |
| 34_D   | 69_D | 3_D | 79_D | 8_D | 80_D | 23_D | 24_D |

1 I/O

| page 2 |      |      |      |     |      |      |      |
|--------|------|------|------|-----|------|------|------|
| 29     | 32   | 33   | 40   | 44  | 52   | 56   | 60   |
| 88_D   | 90_D | 28_D | 74_D | 9_D | 76_D | 81_D | 64_D |

1 I/O

| page 3 |      |     |      |      |      |      |      |
|--------|------|-----|------|------|------|------|------|
| 61     | 63   | 67  | 71   | 72   | 73   | 78   | 79   |
| 75_D   | 82_D | 1_D | 67_D | 77_D | 89_D | 65_D | 12_D |

1 I/O

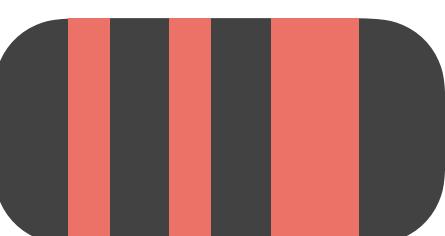
| page 4 |      |      |     |      |      |      |      |
|--------|------|------|-----|------|------|------|------|
| 80     | 84   | 86   | 87  | 91   | 94   | 95   | 99   |
| 70_D   | 41_D | 62_D | 7_D | 25_D | 85_D | 59_D | 19_D |

1 I/O

# Realizing Retention-Based Deletes

delete all entries older than  $\leq 65_D$

Data Layout holds the key!



|                               |    |   |    |  |  |  |  |  |
|-------------------------------|----|---|----|--|--|--|--|--|
| $S_{min}=1 :: S_{max}=99$     |    |   |    |  |  |  |  |  |
| $D_{min}=1_D :: D_{max}=90_D$ |    |   |    |  |  |  |  |  |
| page 1                        |    |   |    |  |  |  |  |  |
| $S_{min}=1 :: S_{max}=24$     |    |   |    |  |  |  |  |  |
| $D_{min}=3_D :: D_{max}=80_D$ |    |   |    |  |  |  |  |  |
| page 2                        |    |   |    |  |  |  |  |  |
| $S_{min}=29 :: S_{max}=60$    |    |   |    |  |  |  |  |  |
| $D_{min}=9_D :: D_{max}=90_D$ |    |   |    |  |  |  |  |  |
| 3                             |    |   |    |  |  |  |  |  |
| 0                             | 01 | 0 | 70 |  |  |  |  |  |

| page 1 |      |     |      |     |      |      |      |
|--------|------|-----|------|-----|------|------|------|
| 1      | 4    | 9   | 14   | 15  | 19   | 20   | 24   |
| 34_D   | 69_D | 3_D | 79_D | 8_D | 80_D | 23_D | 24_D |

1 I/O

| page 2 |      |      |      |     |      |      |      |
|--------|------|------|------|-----|------|------|------|
| 29     | 32   | 33   | 40   | 44  | 52   | 56   | 60   |
| 88_D   | 90_D | 28_D | 74_D | 9_D | 76_D | 81_D | 64_D |

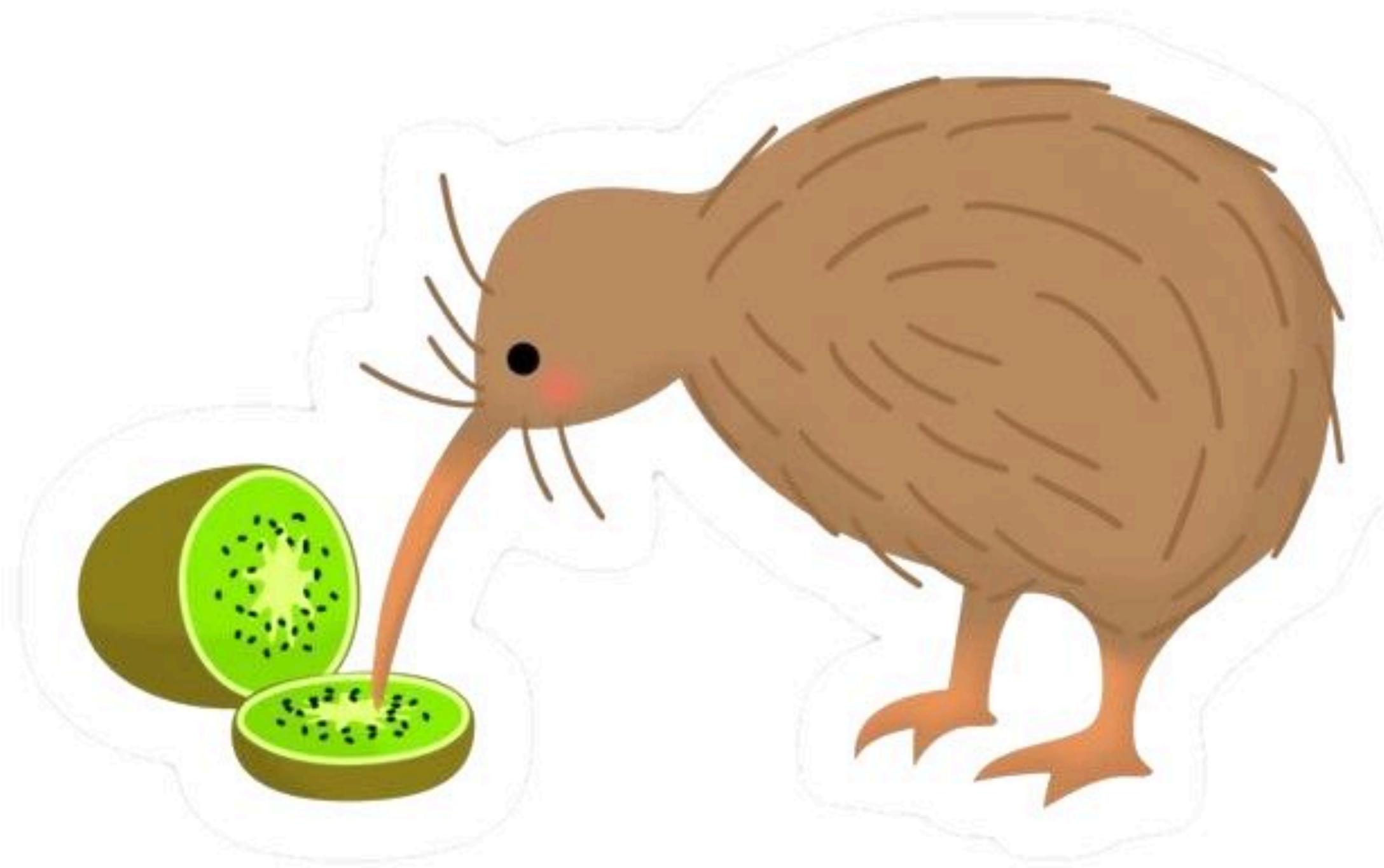
1 I/O

|      |      |      |     |      |      |      |      |    |
|------|------|------|-----|------|------|------|------|----|
| 66   | 67   | 68   | 69  | 70   | 71   | 72   | 73   | 74 |
| 70_D | 41_D | 62_D | 7_D | 25_D | 85_D | 59_D | 19_D |    |

1 I/O

1 I/O

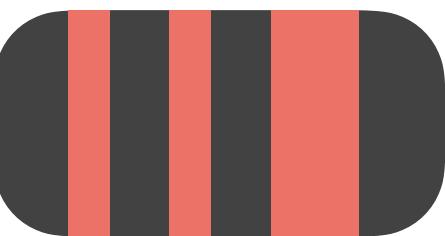
# Realizing Retention-Based Deletes



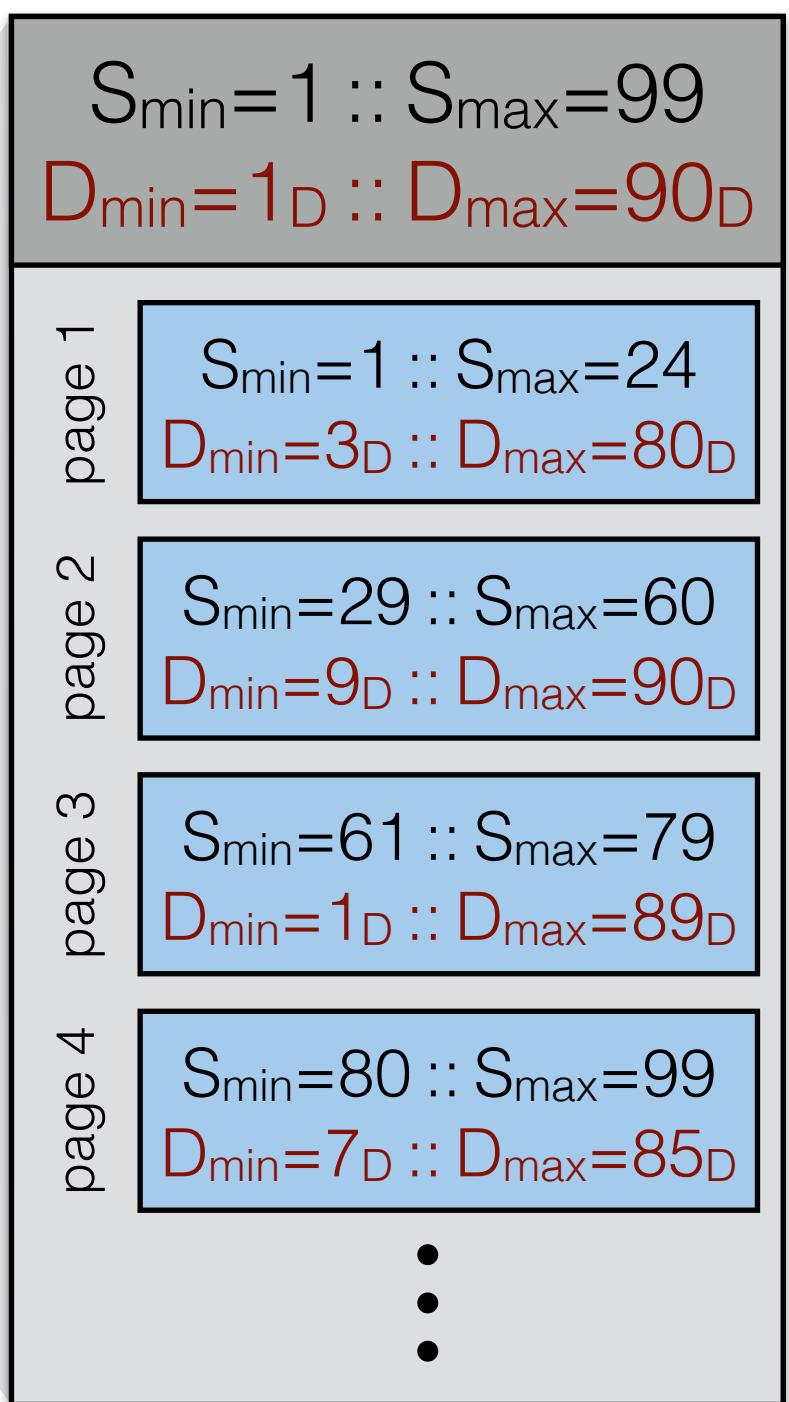
KiWi  
Key Weaving storage layout

# Key Weaving storage layout

delete all entries older than  $\leq 65_D$



SST file

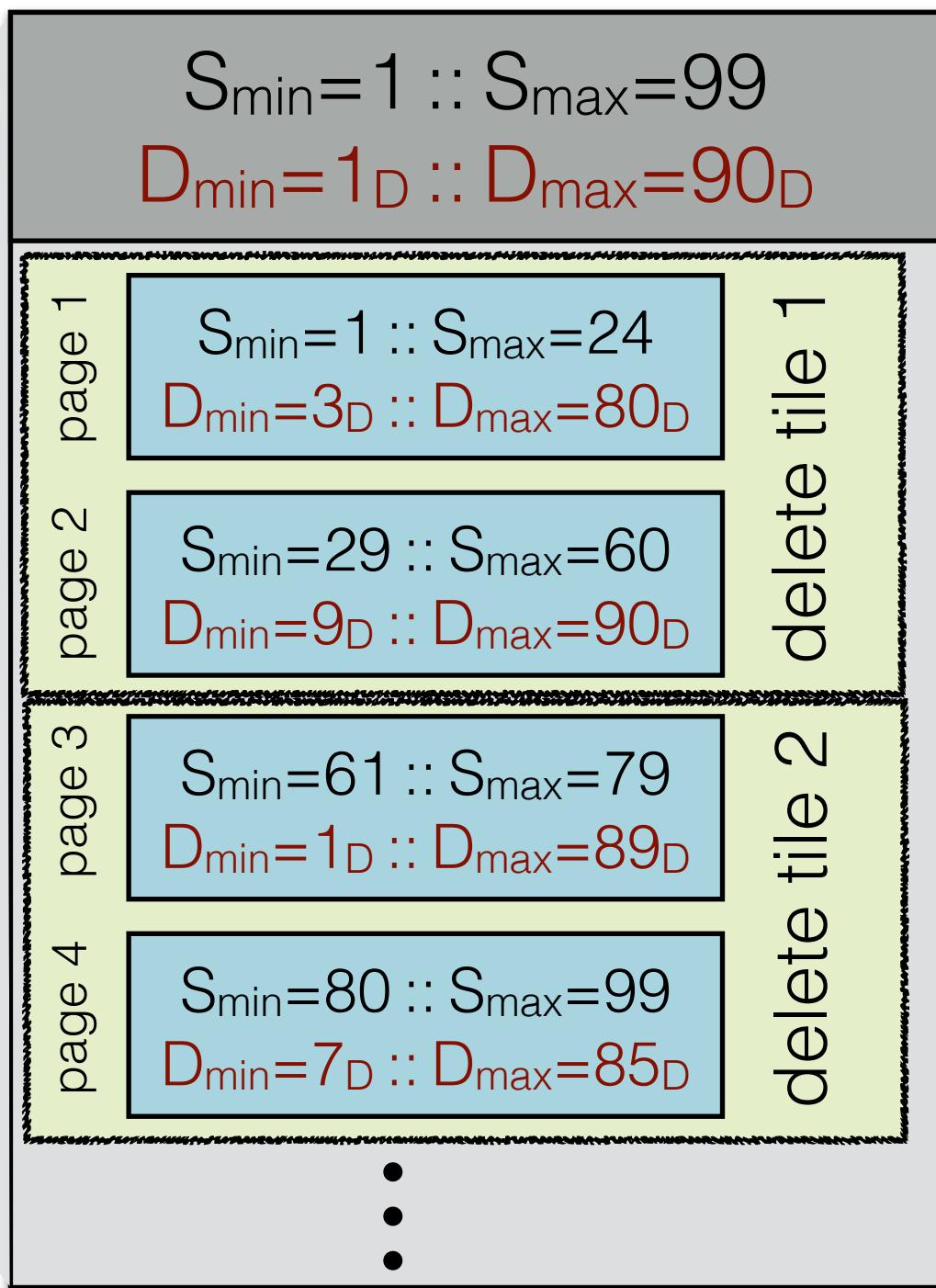


# Key Weaving storage layout

delete all entries older than  $\leq 65_D$



SST file



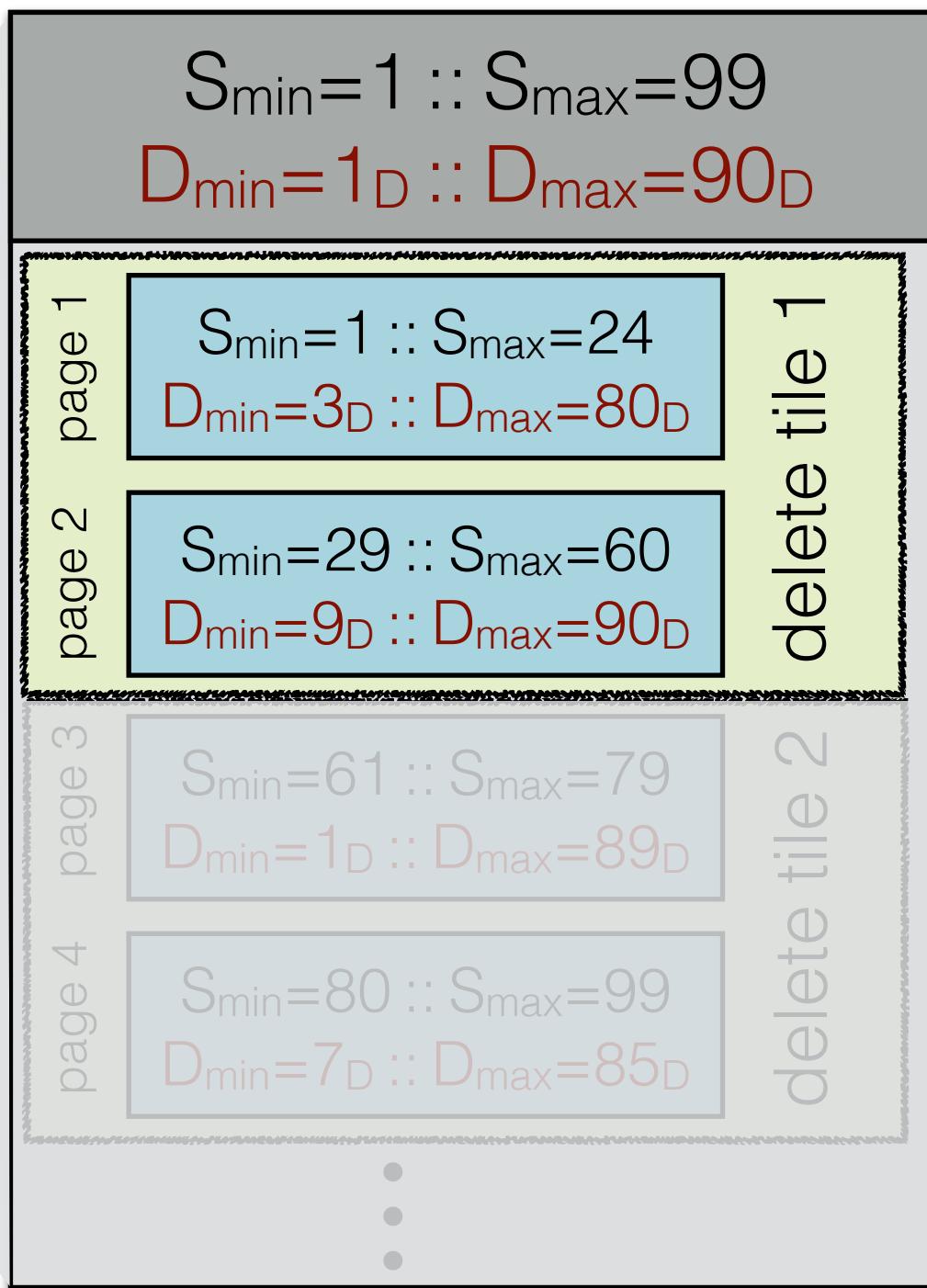
partitioned on  $S$

# Key Weaving storage layout

delete all entries older than  $\leq 65_D$



SST file



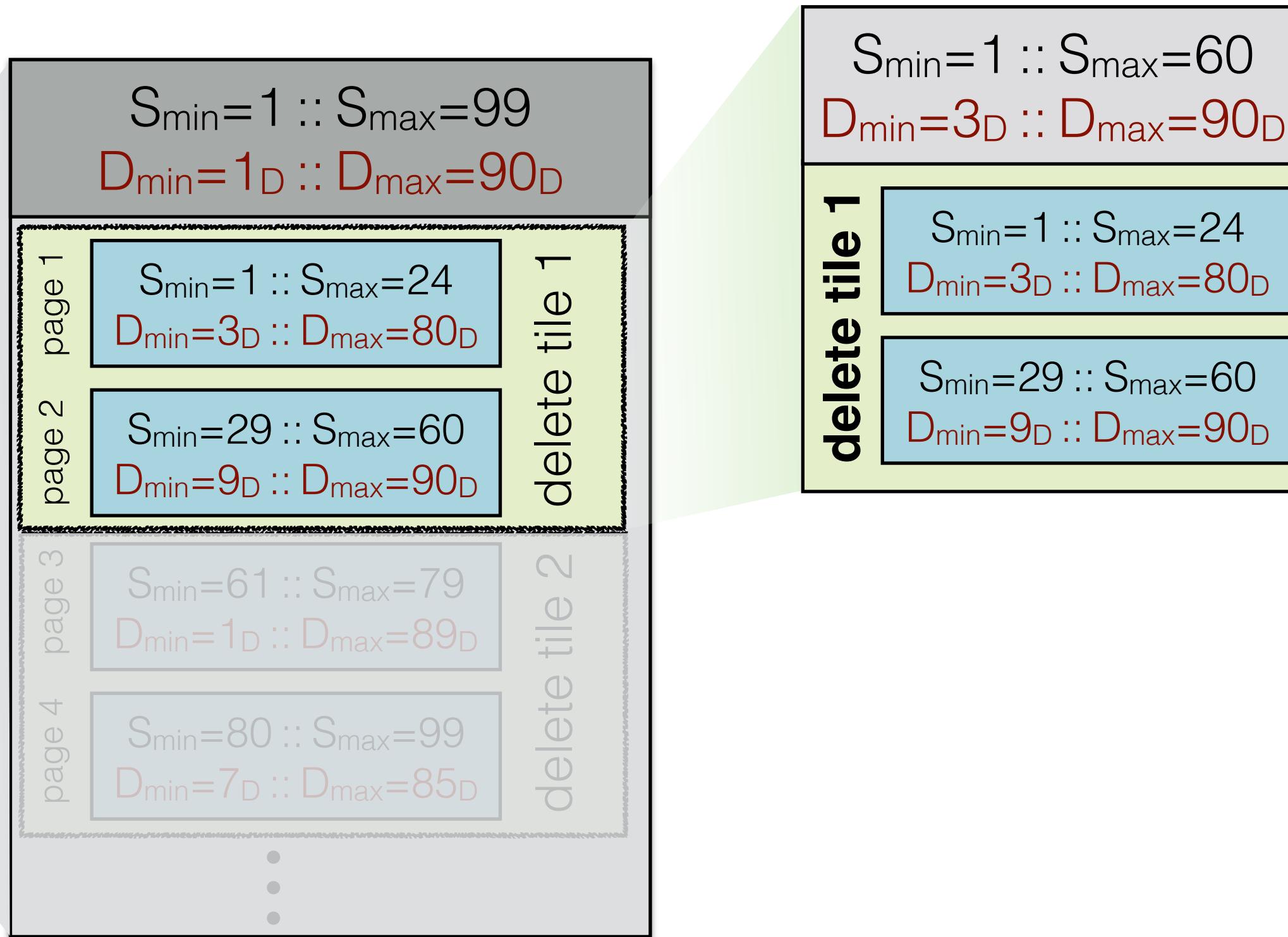
partitioned on  $S$

# Key Weaving storage layout

delete all entries older than  $\leq 65_D$



SST file



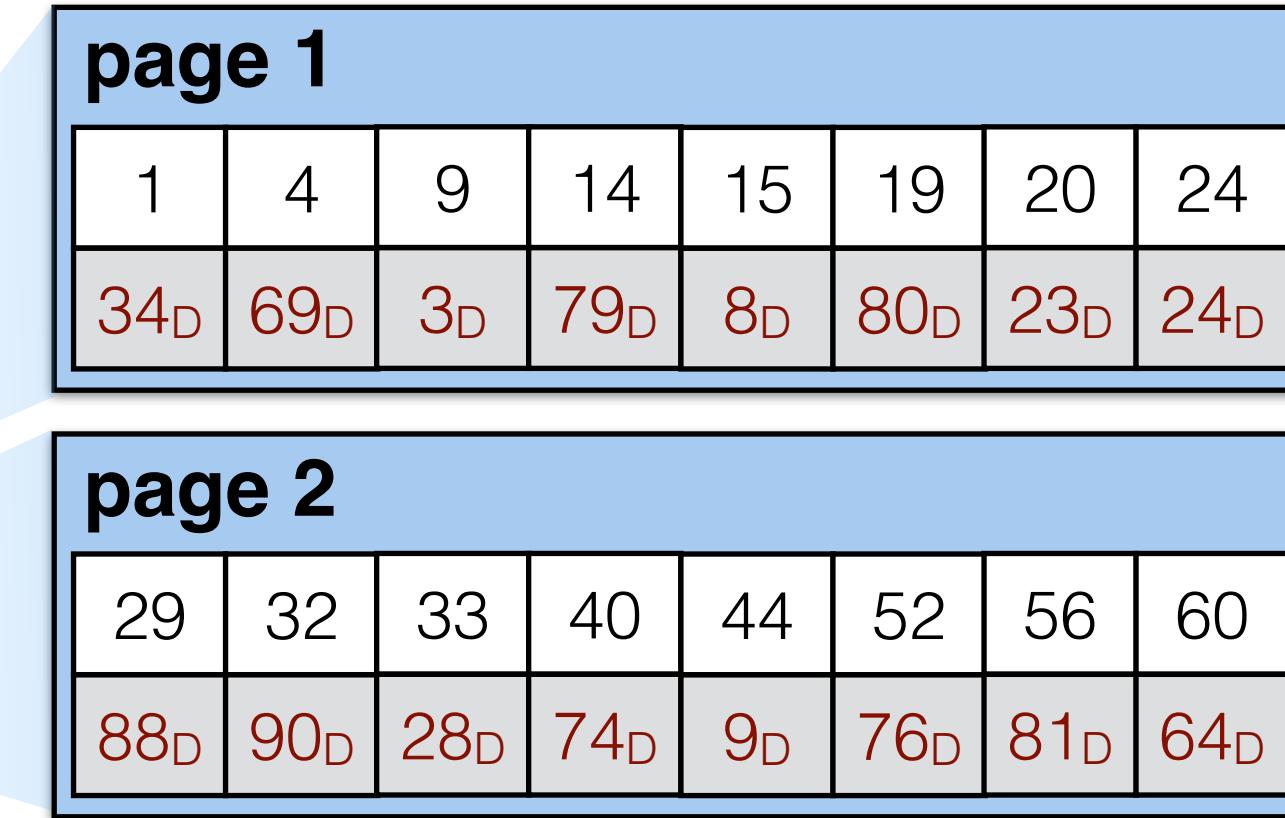
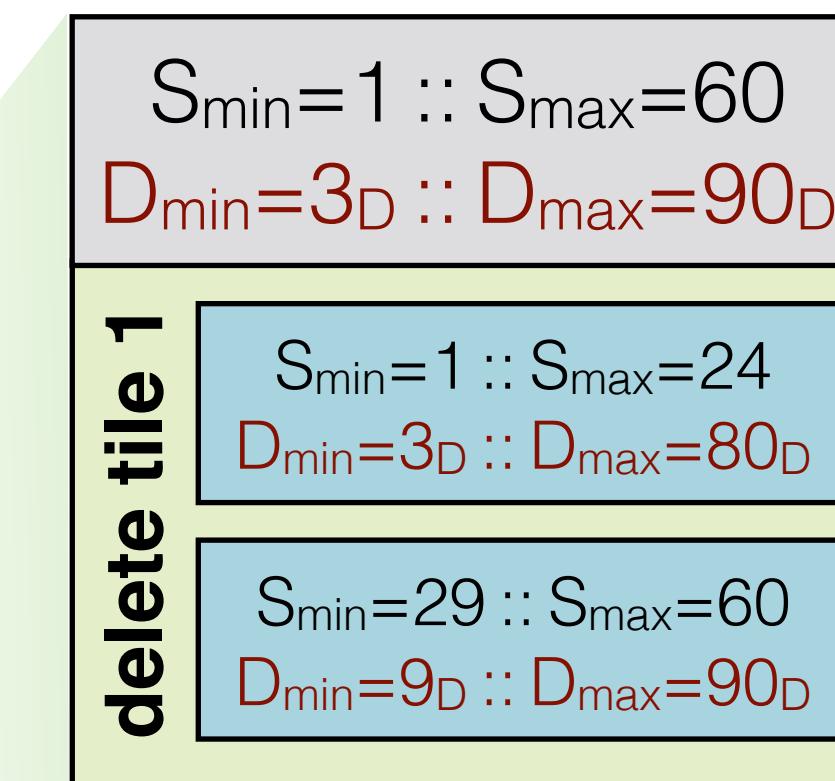
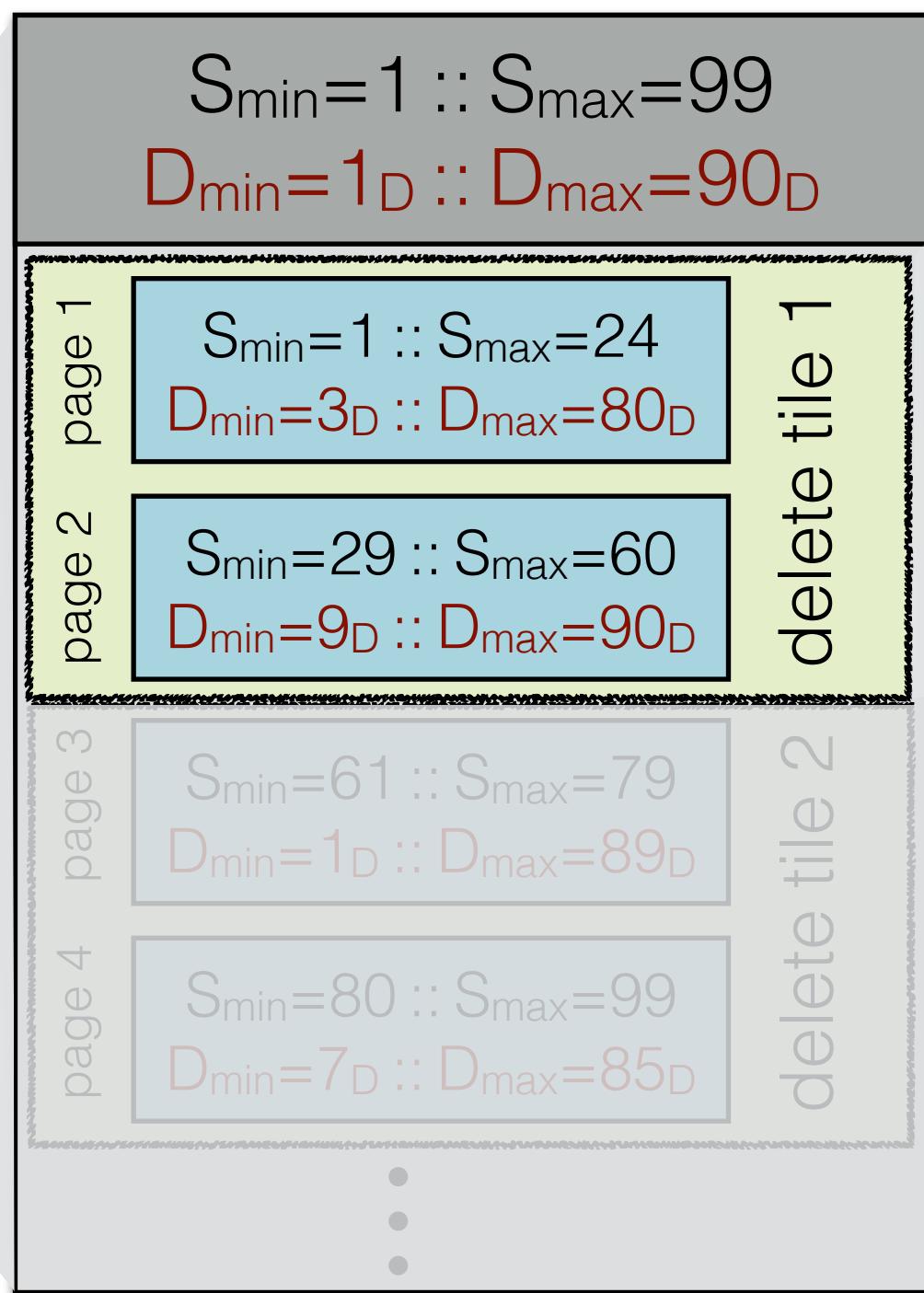
partitioned on  $S$

# Key Weaving storage layout

delete all entries older than  $\leq 65_D$



SST file



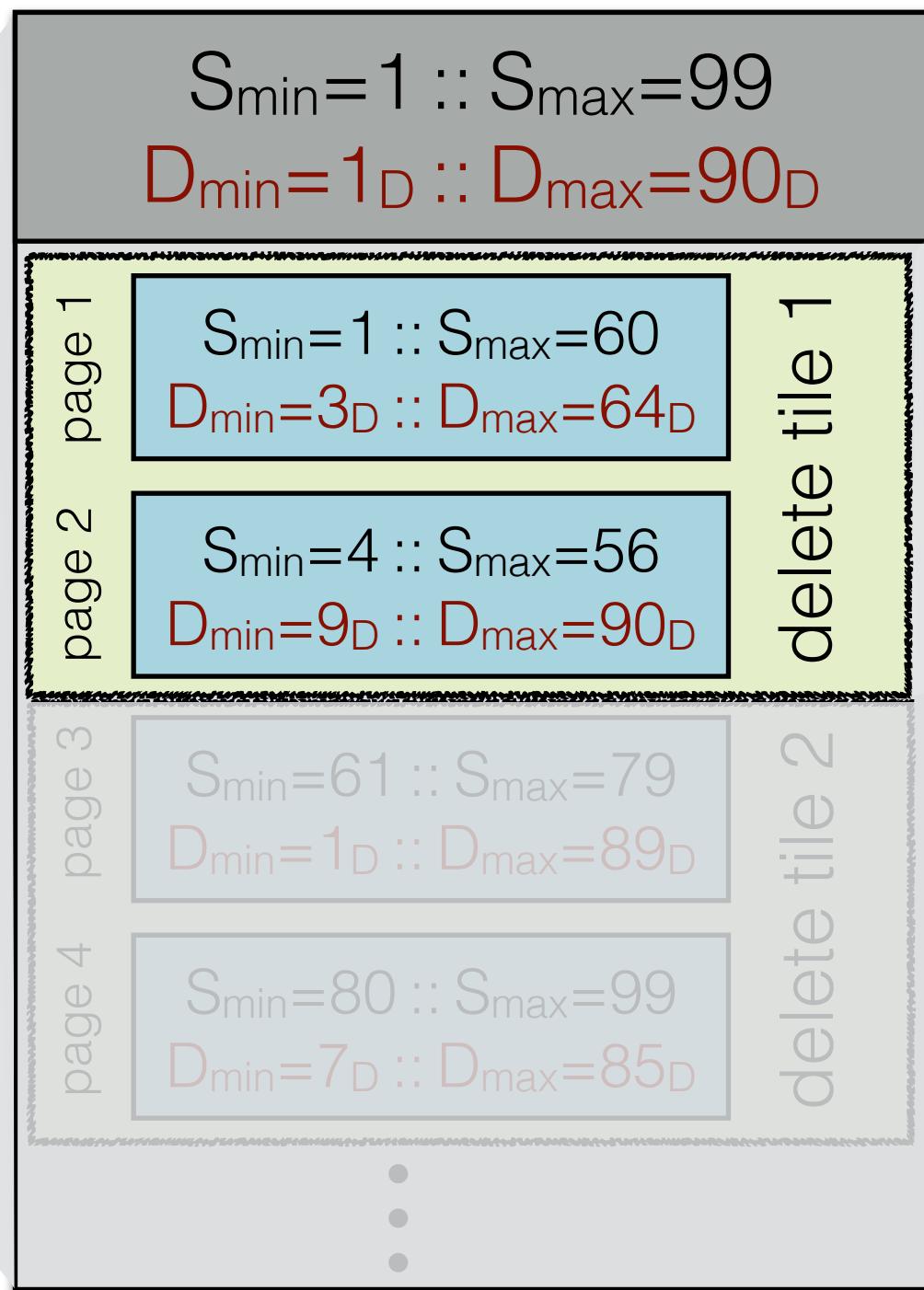
partitioned on  $S$

# Key Weaving storage layout

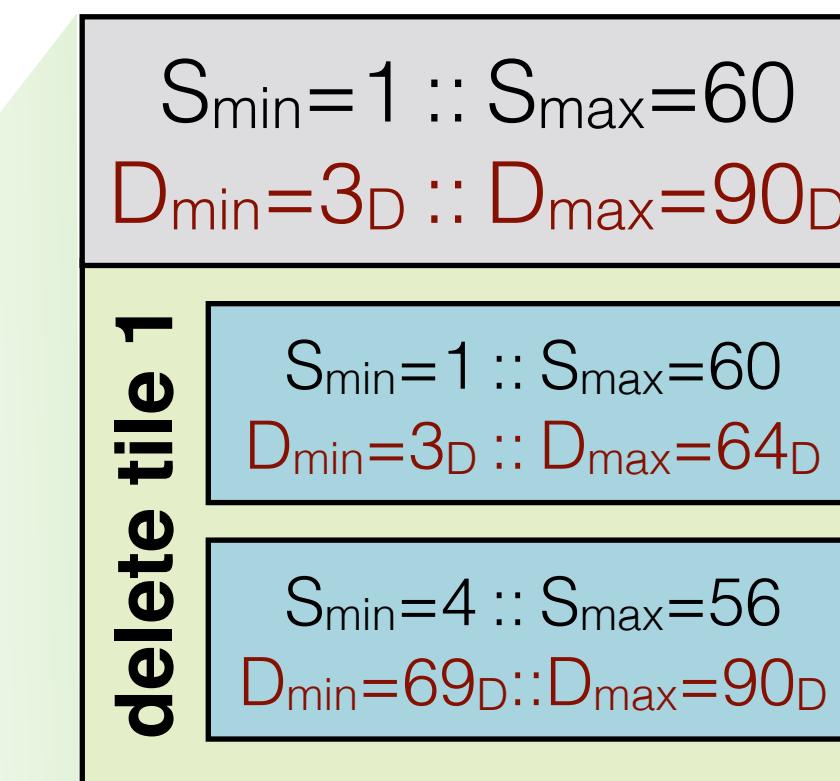
delete all entries older than  $\leq 65_D$



SST file



partitioned on  $S$



partitioned on  $D$

The diagram shows the SST file partitioned by  $D$  after deleting tile 1. It consists of two pages: page 1 and page 2. The tiles are labeled "page 1" and "page 2". The tiles are defined by ranges of S and D values:

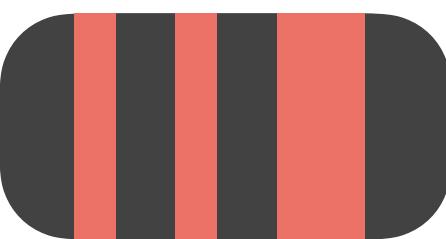
| page 1 |     |     |      |      |      |      |      |
|--------|-----|-----|------|------|------|------|------|
| 9      | 15  | 44  | 20   | 24   | 33   | 1    | 60   |
| 3_D    | 8_D | 9_D | 23_D | 24_D | 28_D | 34_D | 64_D |

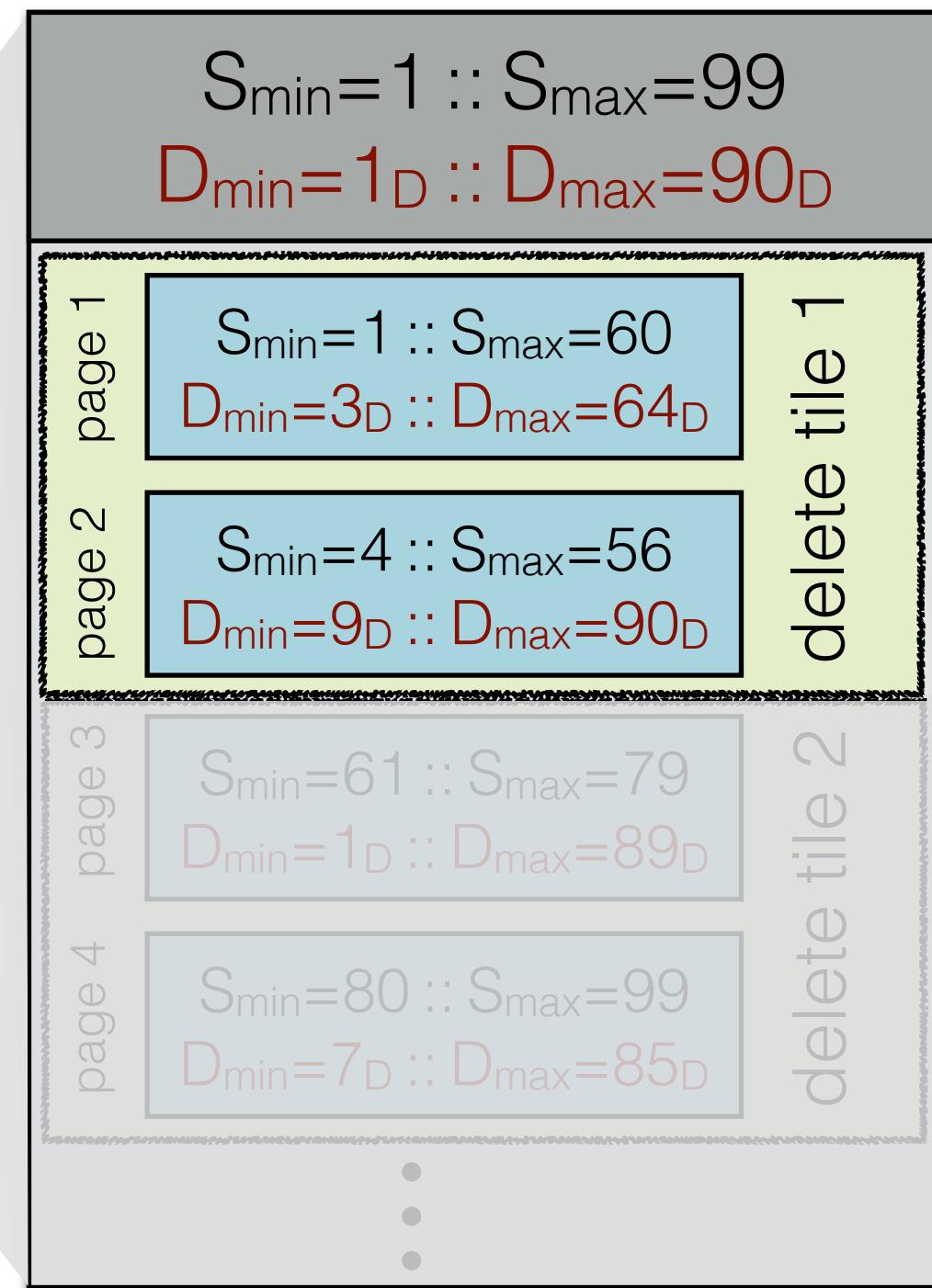
| page 2 |      |      |      |      |      |      |      |
|--------|------|------|------|------|------|------|------|
| 4      | 40   | 52   | 14   | 19   | 56   | 29   | 32   |
| 69_D   | 74_D | 76_D | 79_D | 80_D | 81_D | 88_D | 90_D |

# Key Weaving storage layout

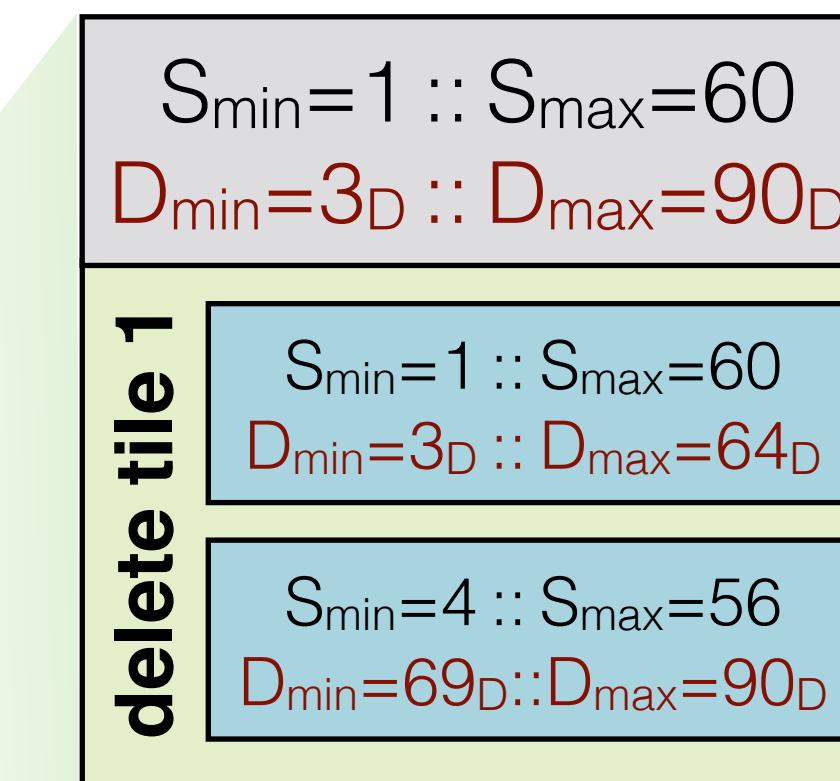
delete all entries older than  $\leq 65_D$



SST file



partitioned on S



partitioned on D

The diagram shows a page layout with two pages. A red shaded area highlights the first page, labeled "drop page".

| page 1 |     |     |      |      |      |      |      |
|--------|-----|-----|------|------|------|------|------|
| 9      | 15  | 44  | 20   | 24   | 33   | 1    | 60   |
| 3_D    | 8_D | 9_D | 23_D | 24_D | 28_D | 34_D | 64_D |

| page 2 |      |      |      |      |      |      |      |
|--------|------|------|------|------|------|------|------|
| 4      | 40   | 52   | 14   | 19   | 56   | 29   | 32   |
| 69_D   | 74_D | 76_D | 79_D | 80_D | 81_D | 88_D | 90_D |

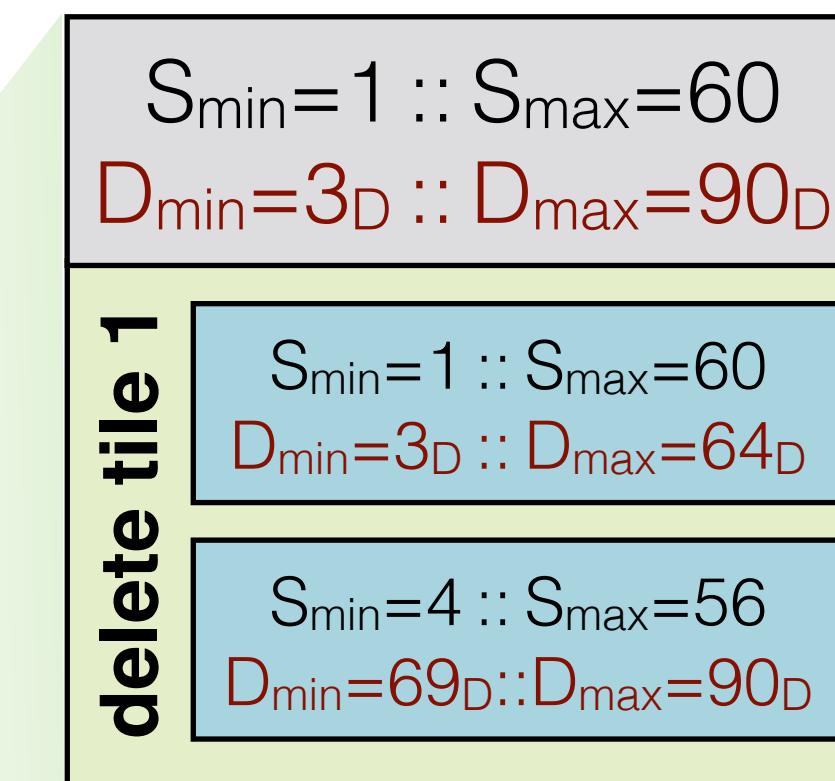
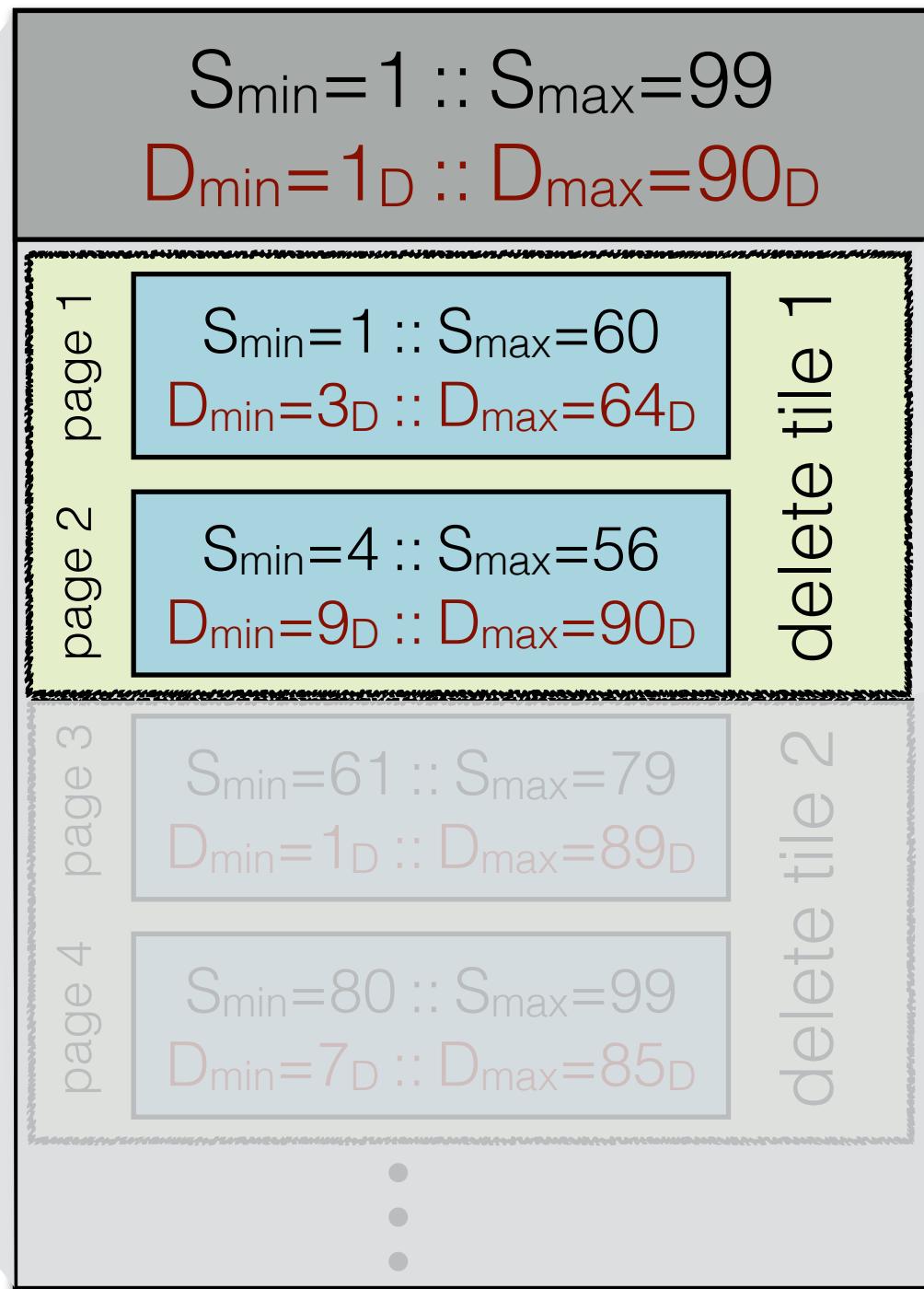
drop page

# Key Weaving storage layout

delete all entries older than  $\leq 65_D$



SST file



sorted on S

drop page

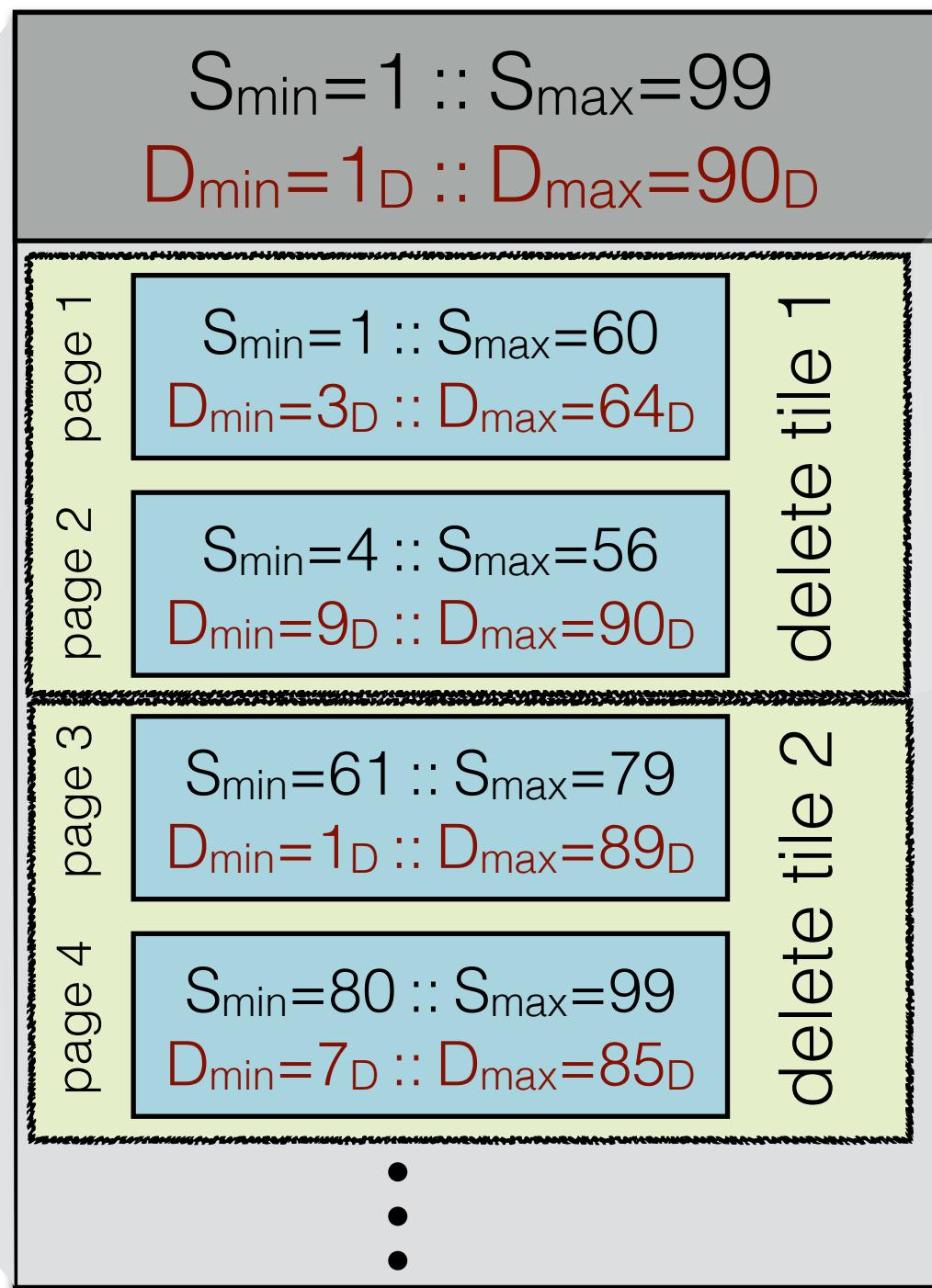
|        |        |        |        |        |        |        |        |
|--------|--------|--------|--------|--------|--------|--------|--------|
| page 1 |        |        |        |        |        |        |        |
| 1      | 9      | 15     | 20     | 24     | 33     | 44     | 60     |
| $34_D$ | $3_D$  | $8_D$  | $23_D$ | $24_D$ | $28_D$ | $9_D$  | $64_D$ |
| page 2 |        |        |        |        |        |        |        |
| 4      | 14     | 19     | 29     | 32     | 40     | 52     | 56     |
| $69_D$ | $79_D$ | $80_D$ | $88_D$ | $90_D$ | $74_D$ | $76_D$ | $81_D$ |

# Key Weaving storage layout

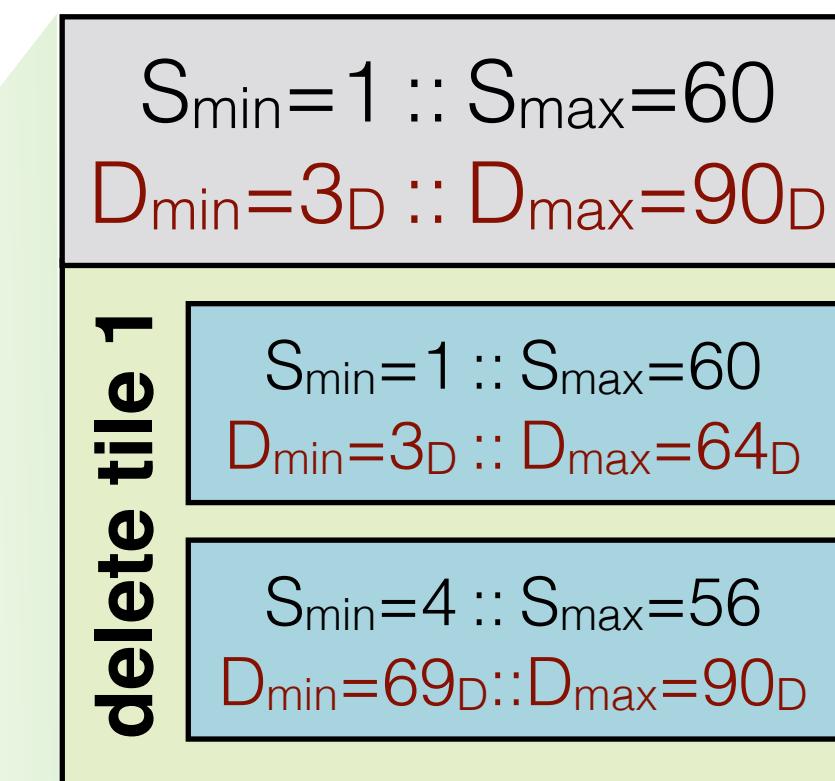
delete all entries older than  $\leq 65_D$



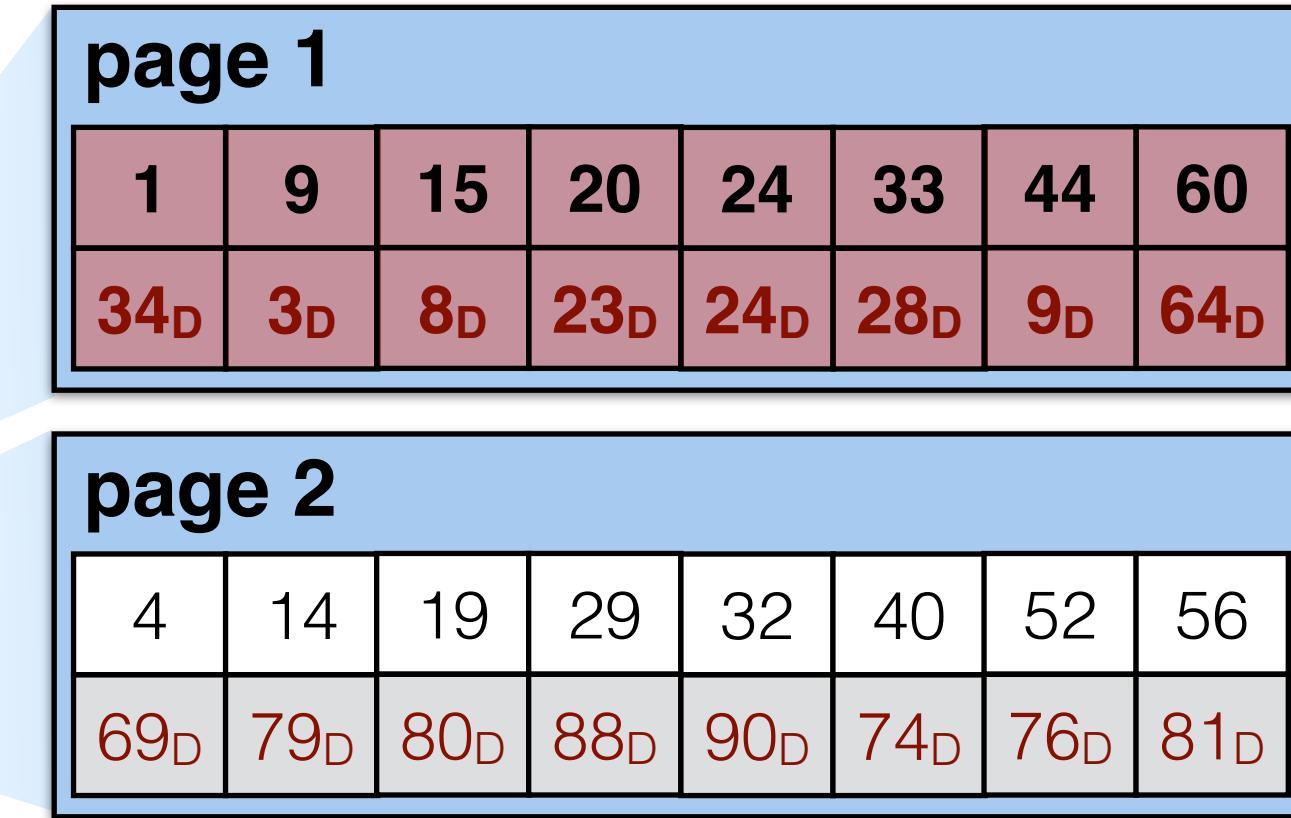
SST file



partitioned on  $S$



partitioned on  $D$

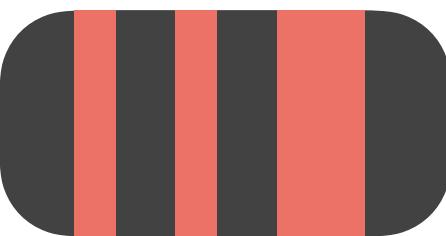


sorted on  $S$

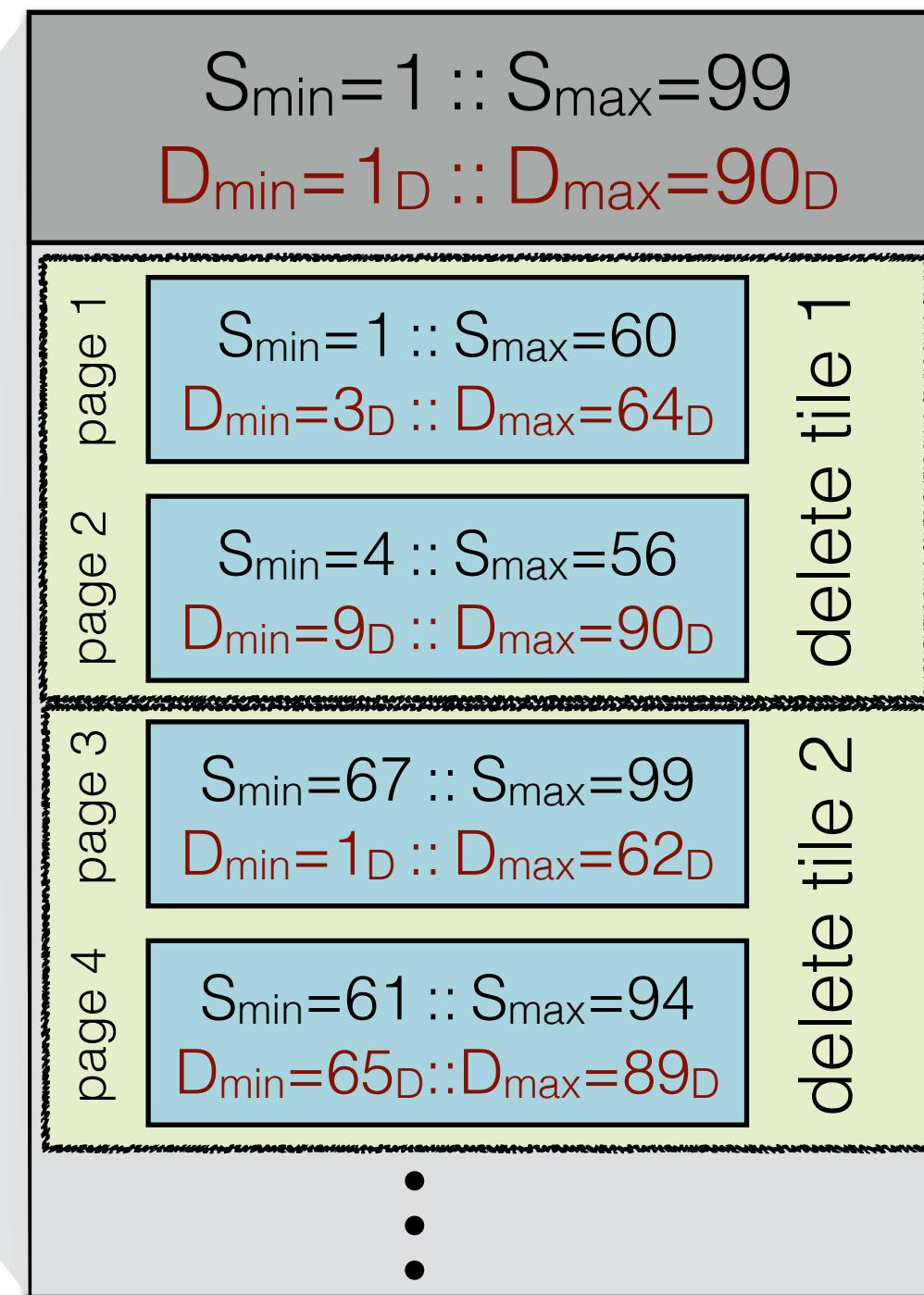
drop  
page

# Key Weaving storage layout

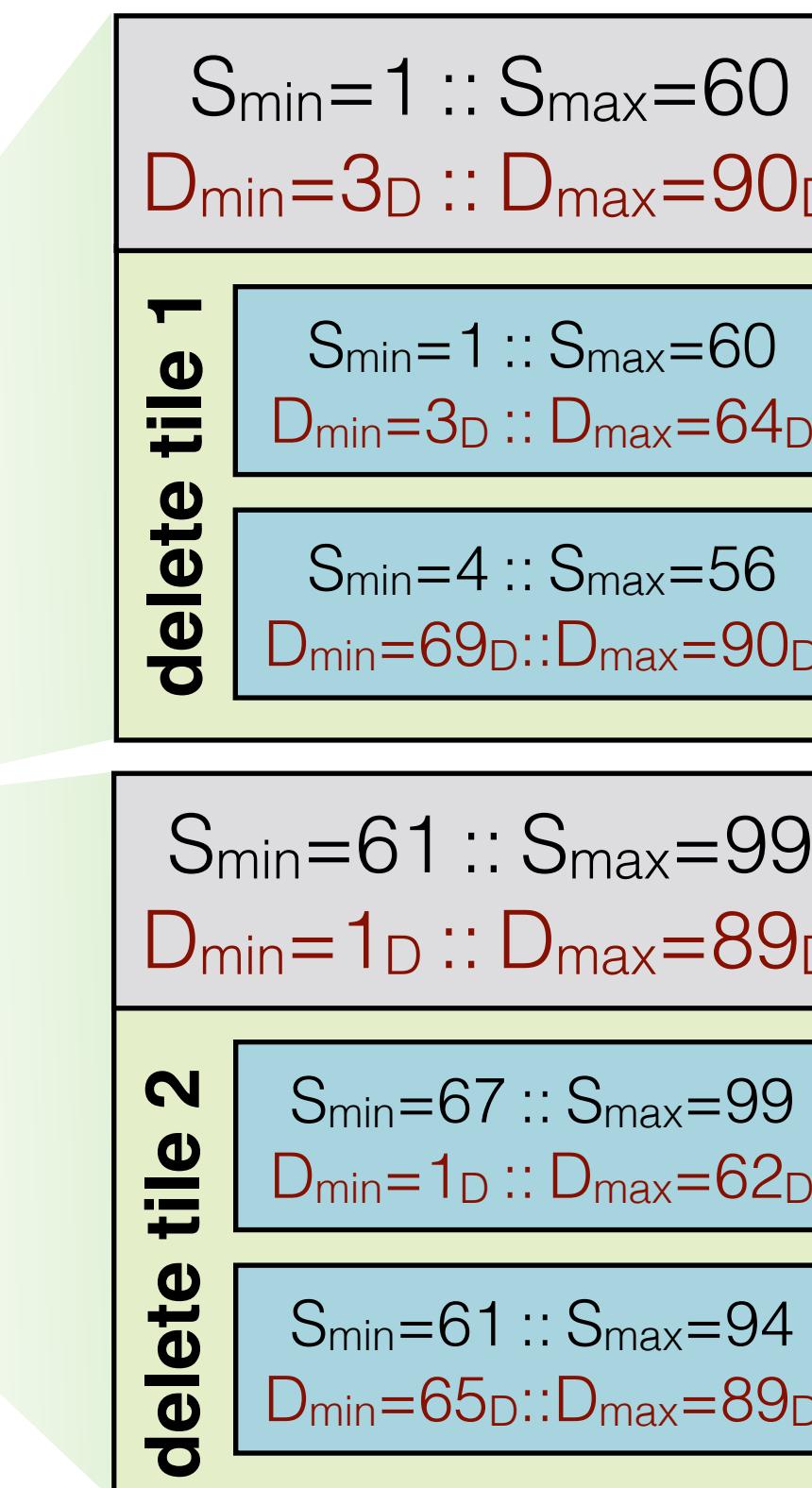
delete all entries older than  $\leq 65_D$



SST file



partitioned on  $S$



partitioned on  $D$

The storage layout is sorted on  $S$ . It contains four pages:

- page 1: 1, 9, 15, 20, 24, 33, 44, 60;  $34_D$ ,  $3_D$ ,  $8_D$ ,  $23_D$ ,  $24_D$ ,  $28_D$ ,  $9_D$ ,  $64_D$
- page 2: 4, 14, 19, 29, 32, 40, 52, 56;  $69_D$ ,  $79_D$ ,  $80_D$ ,  $88_D$ ,  $90_D$ ,  $74_D$ ,  $76_D$ ,  $81_D$
- page 3: 67, 79, 84, 86, 87, 91, 95, 99;  $1_D$ ,  $12_D$ ,  $41_D$ ,  $62_D$ ,  $7_D$ ,  $25_D$ ,  $59_D$ ,  $19_D$
- page 4: 61, 63, 71, 72, 73, **78**, 80, 94;  $75_D$ ,  $82_D$ ,  $67_D$ ,  $77_D$ ,  $89_D$ ,  $65_D$ ,  $70_D$ ,  $85_D$

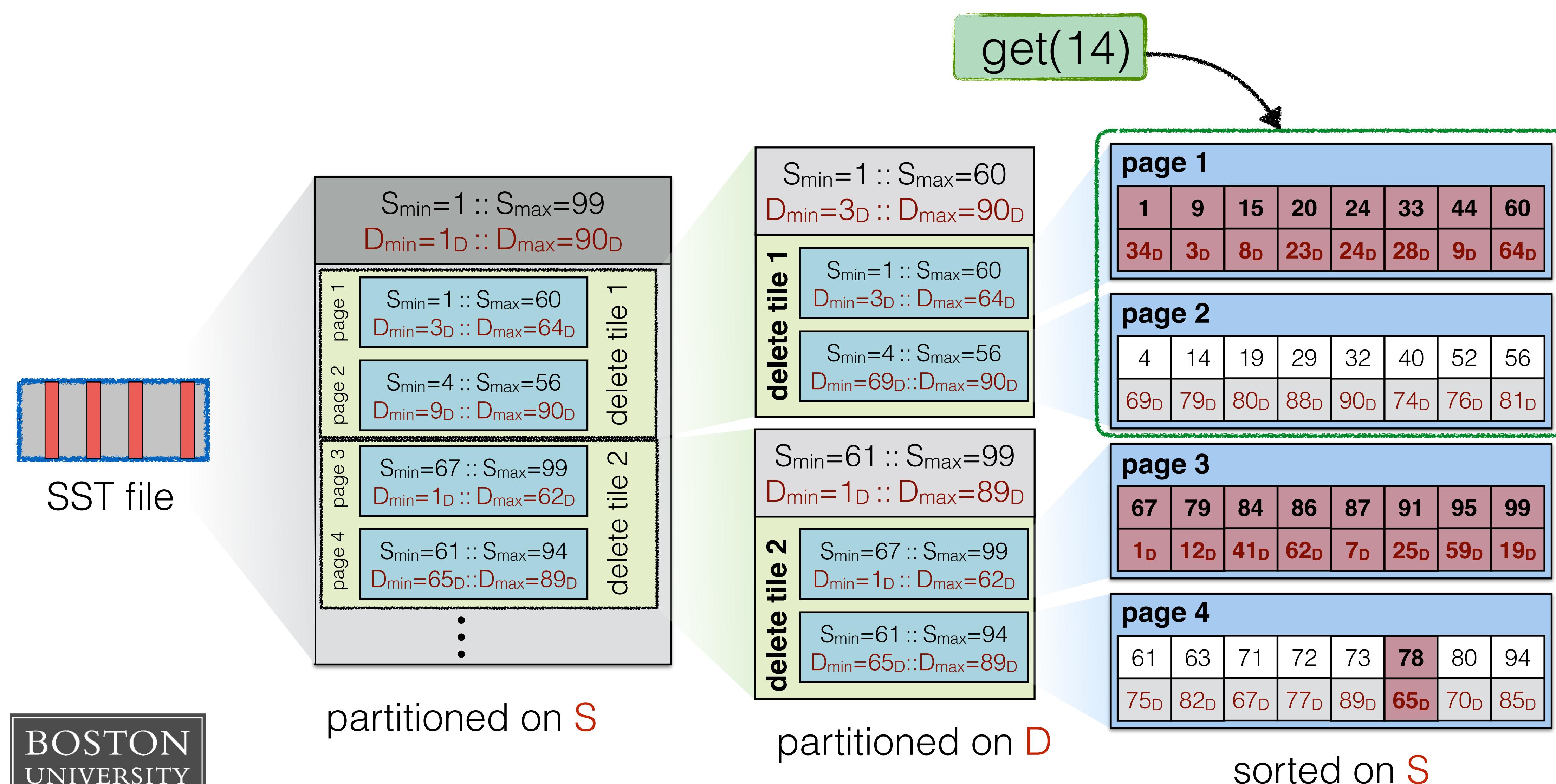
sorted on  $S$

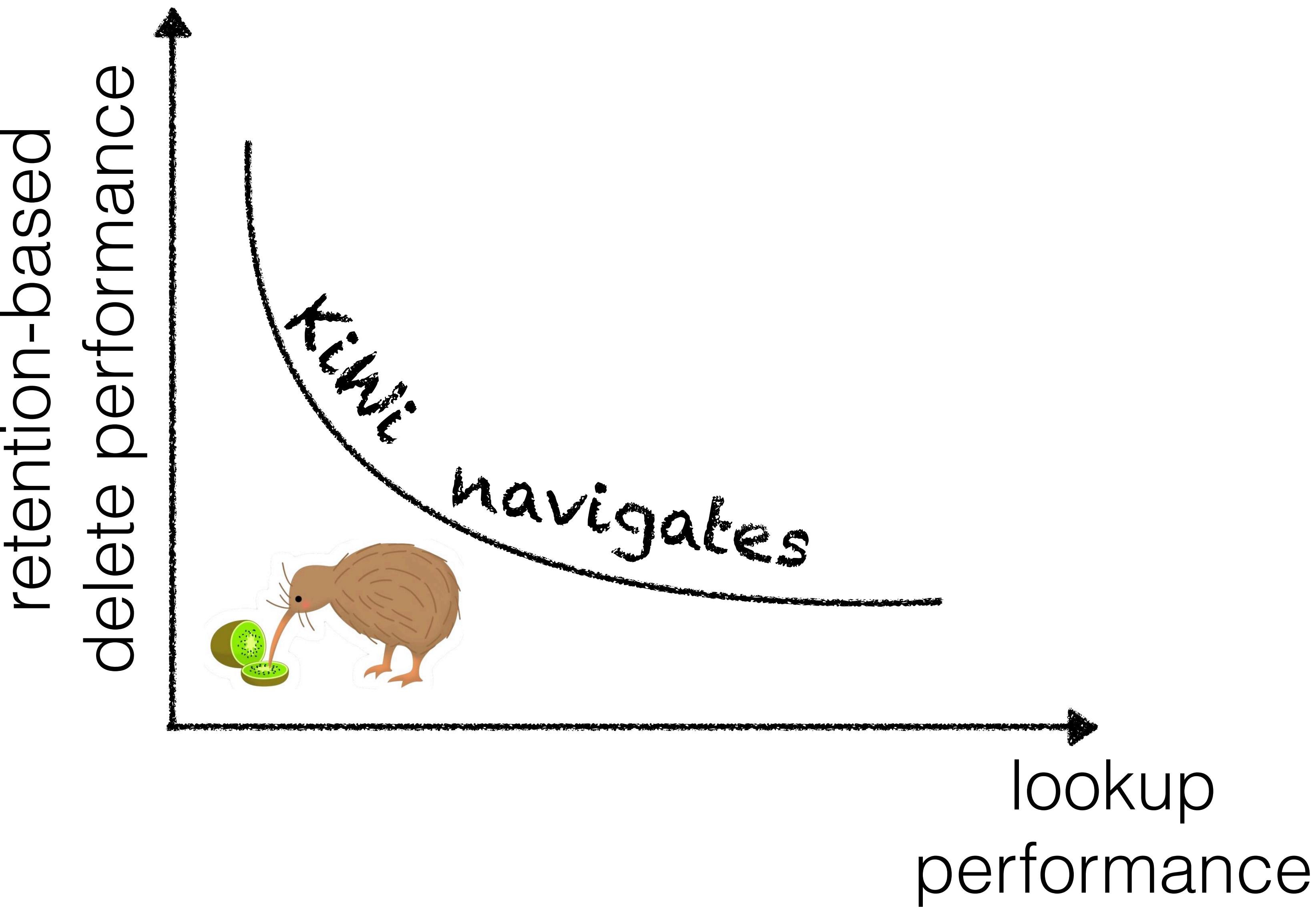
drop page

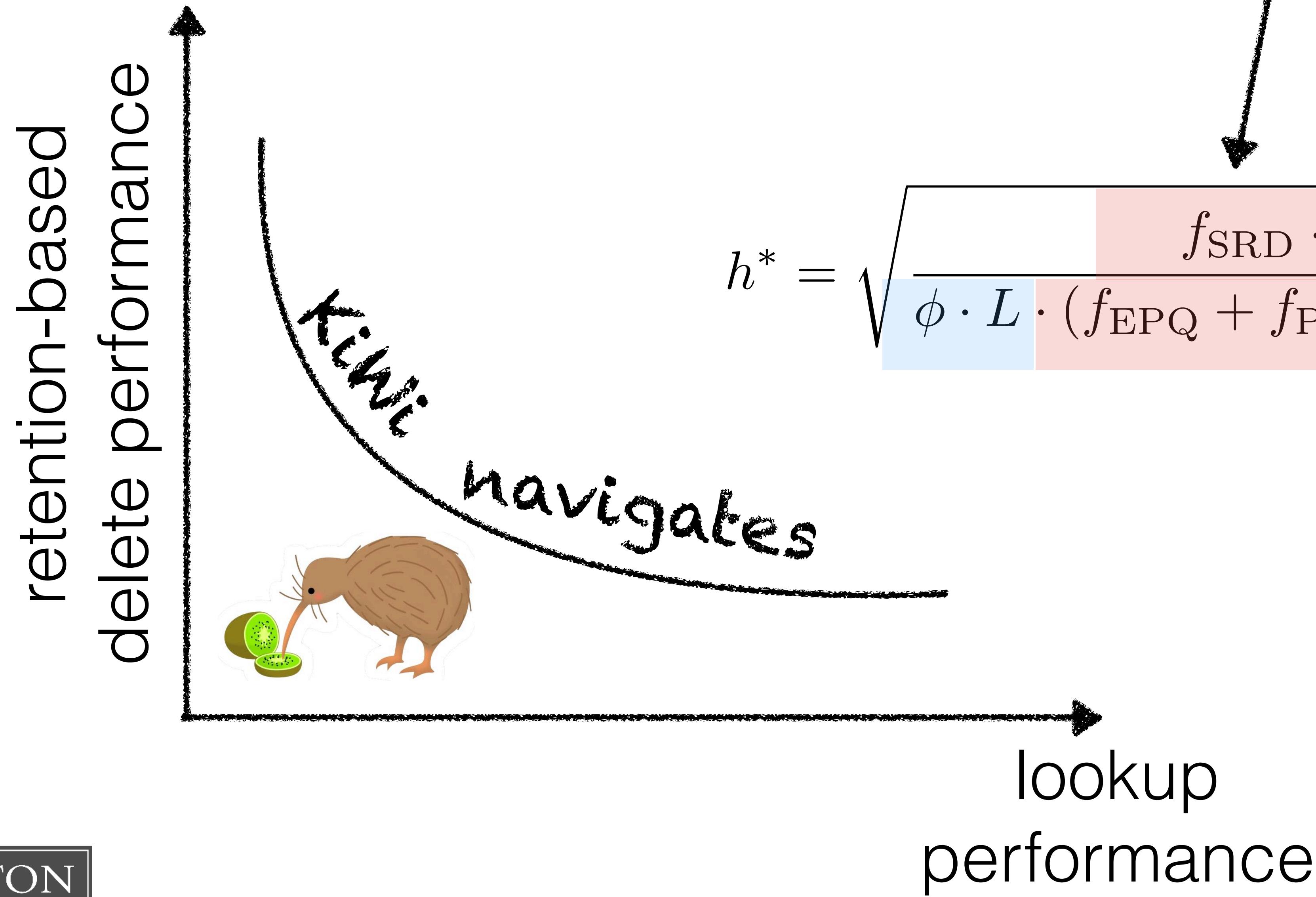
drop page

1 I/O

# Key Weaving storage layout



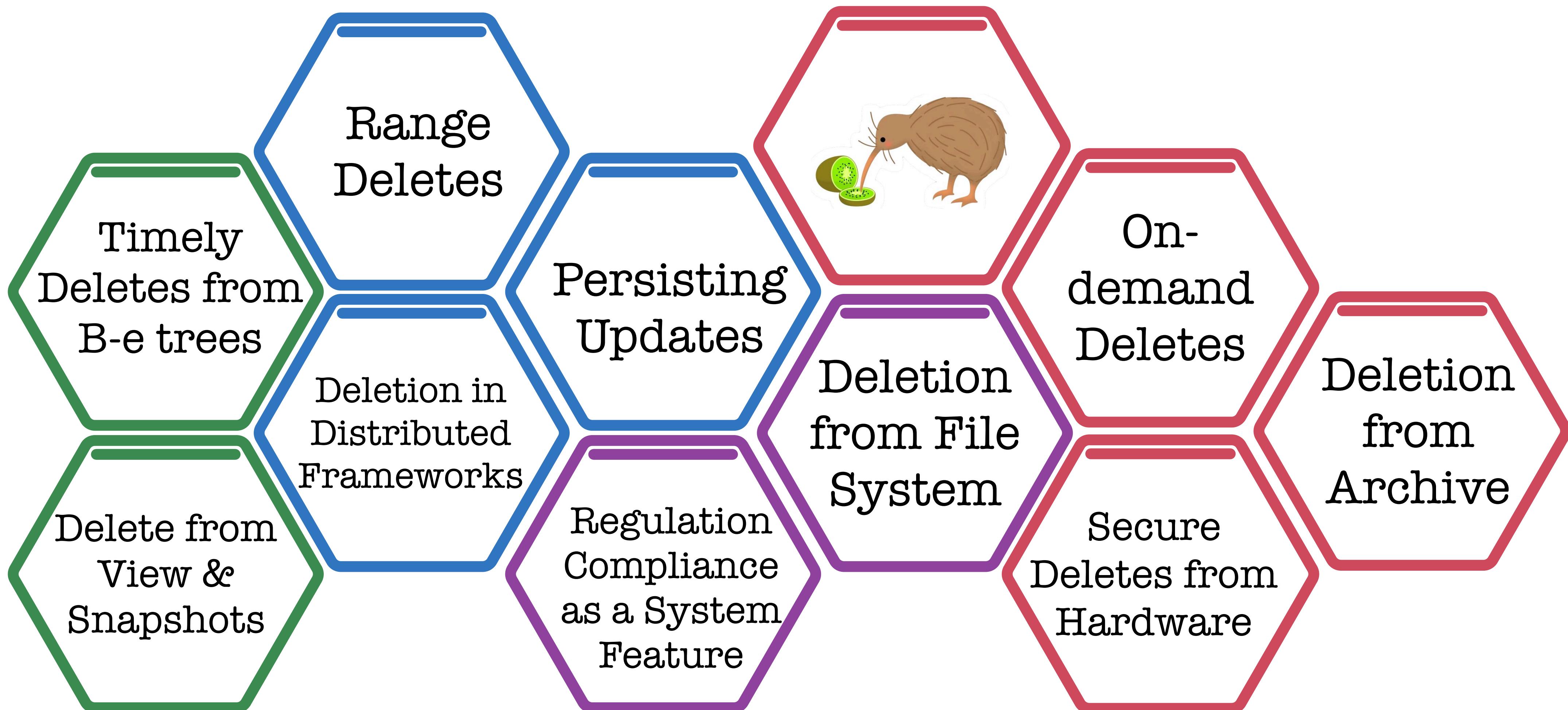




workload

data  
structure

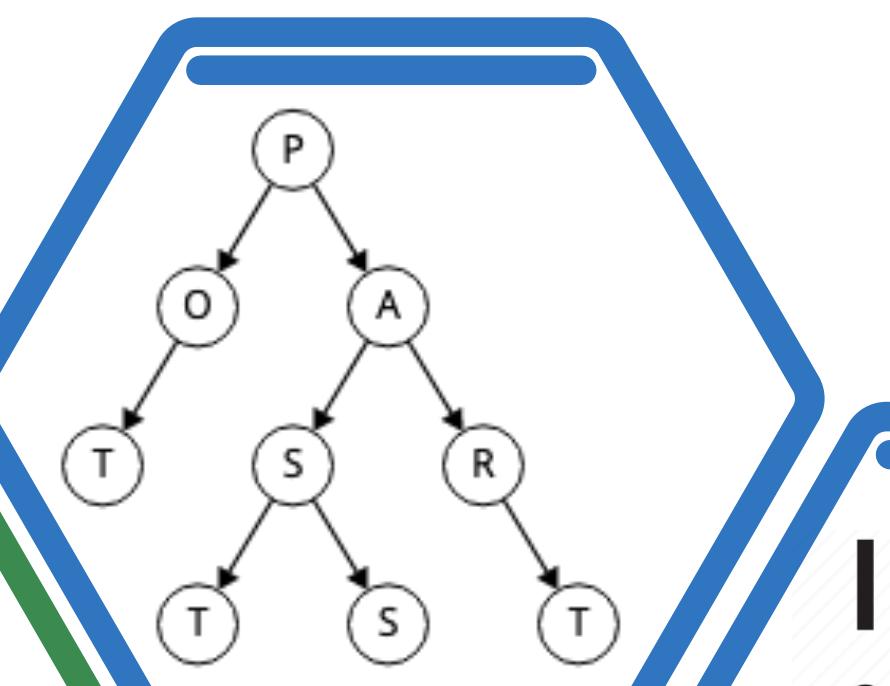
$$h^* = \sqrt{\frac{f_{SRD} \cdot \frac{N}{B}}{\phi \cdot L \cdot (f_{EPQ} + f_{PQ}) + L \cdot f_{SRQ}}}$$





Timely  
Deletes from  
B-e trees

Delete from  
View &  
Snapshots



Deletion in  
Distributed  
Frameworks

100110  
010101  
10 10

Regulation  
Compliance  
as a System  
Feature



Deletion  
from File  
System

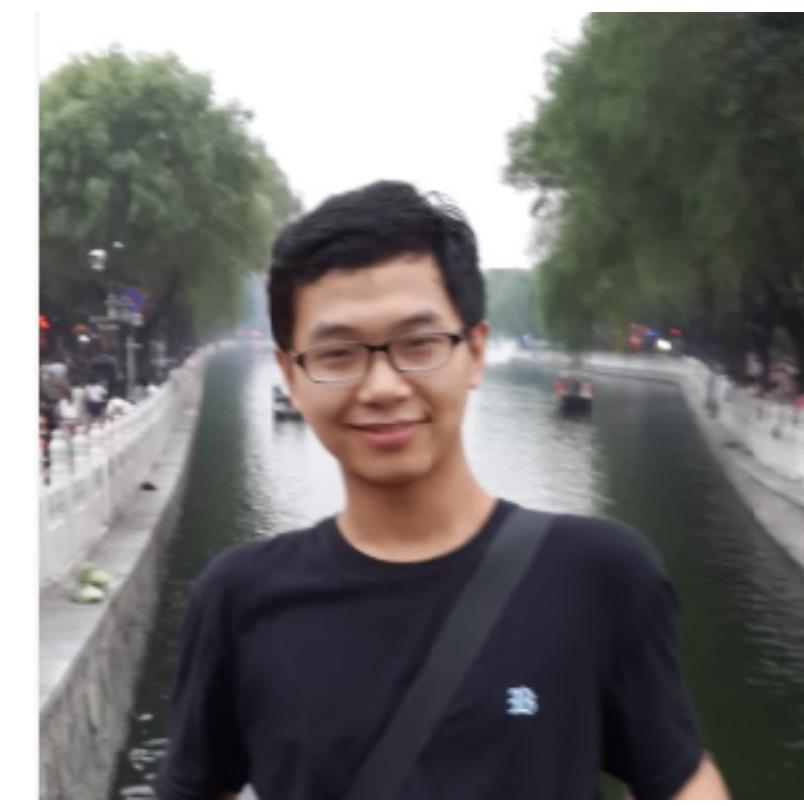
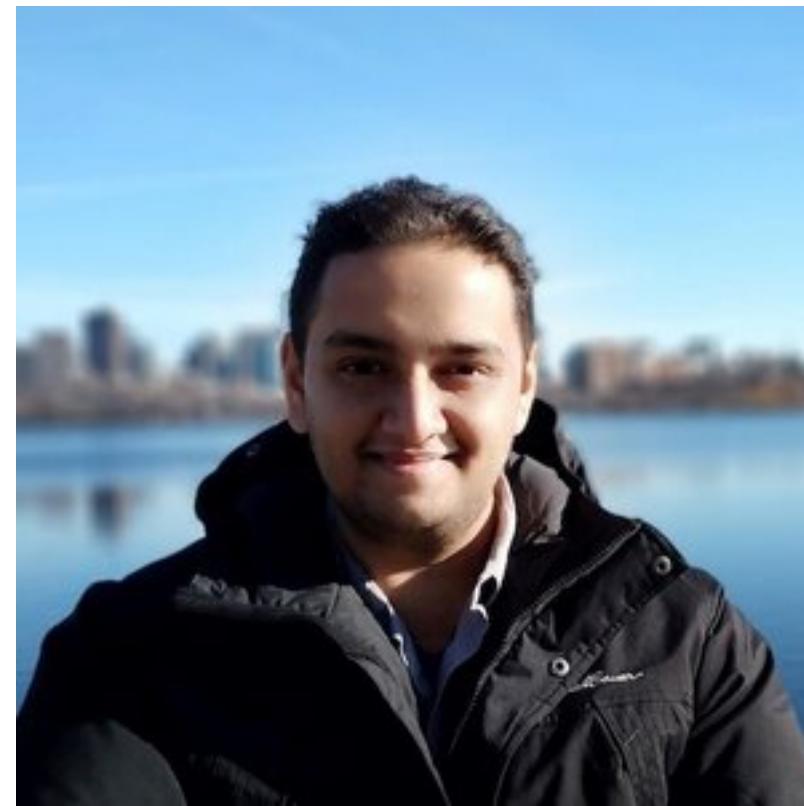


Secure  
Deletes from  
Hardware

Deletion  
from  
Archive

<https://disc.bu.edu/persistent-deletes>

# My Amazing Collaborators



Thank You!

<https://disc.bu.edu/persistent-deletes>