CS 561: Data Systems Architectures

class 23

Learned Indexes

Prof. Manos Athanassoulis

https://bu-disc.github.io/CS561/

with slides from Jialin Ding

Project Submission

April 25th, 11:59pm: *submit draft project report & code*

April 27th and 29th: *3 + 3 20-minute presentations (17+3 for questions)*
(select your slot in piazza)

May 3rd, 11:59pm (hard deadline): *send final report & updated code*

Project Presentations

20 minutes (17+3 for questions)

April 27th

12:30-12:45 Class Evaluation

12:45-1:05 (A) Deal B+-Trees to Support Sortedness by Sean Brady

1:05-1:25 (B) LSM Implementation by Chenming Shi

1:25-1:45 (C) Learned LSM-Trees by Jason Banks

April 29th

12:30-12:50 (D) Query-Driven LSM Compaction by Manish Patel, Chen-Wei Weng, and Al Dahler

12:50-1:10 (E) Bufferpool Implementation by Kaijie Chen

1:10-1:30 (F) Bufferpool Implementation by Haochuan Xiong

1:30-1:45 Closing Remarks

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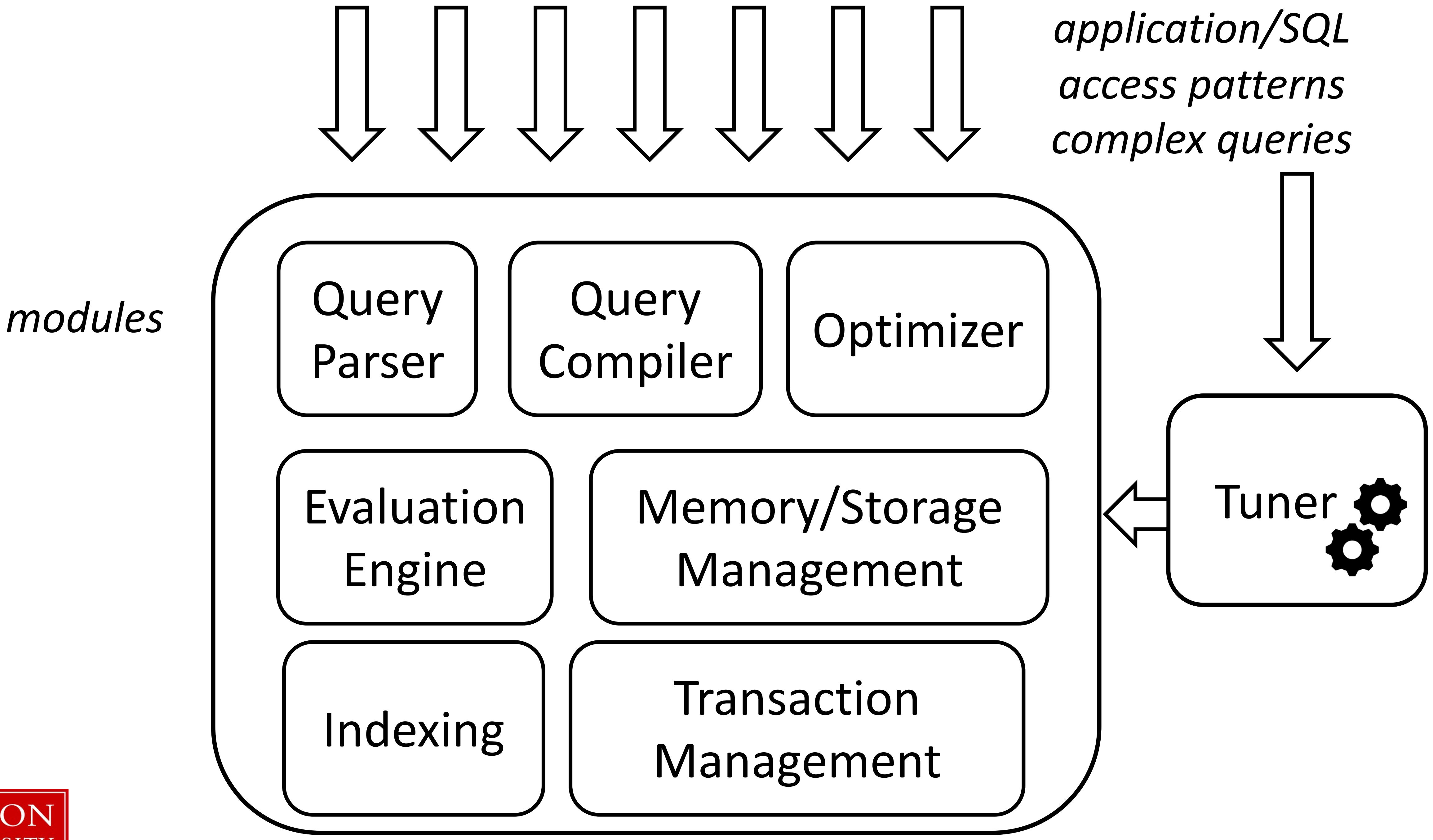

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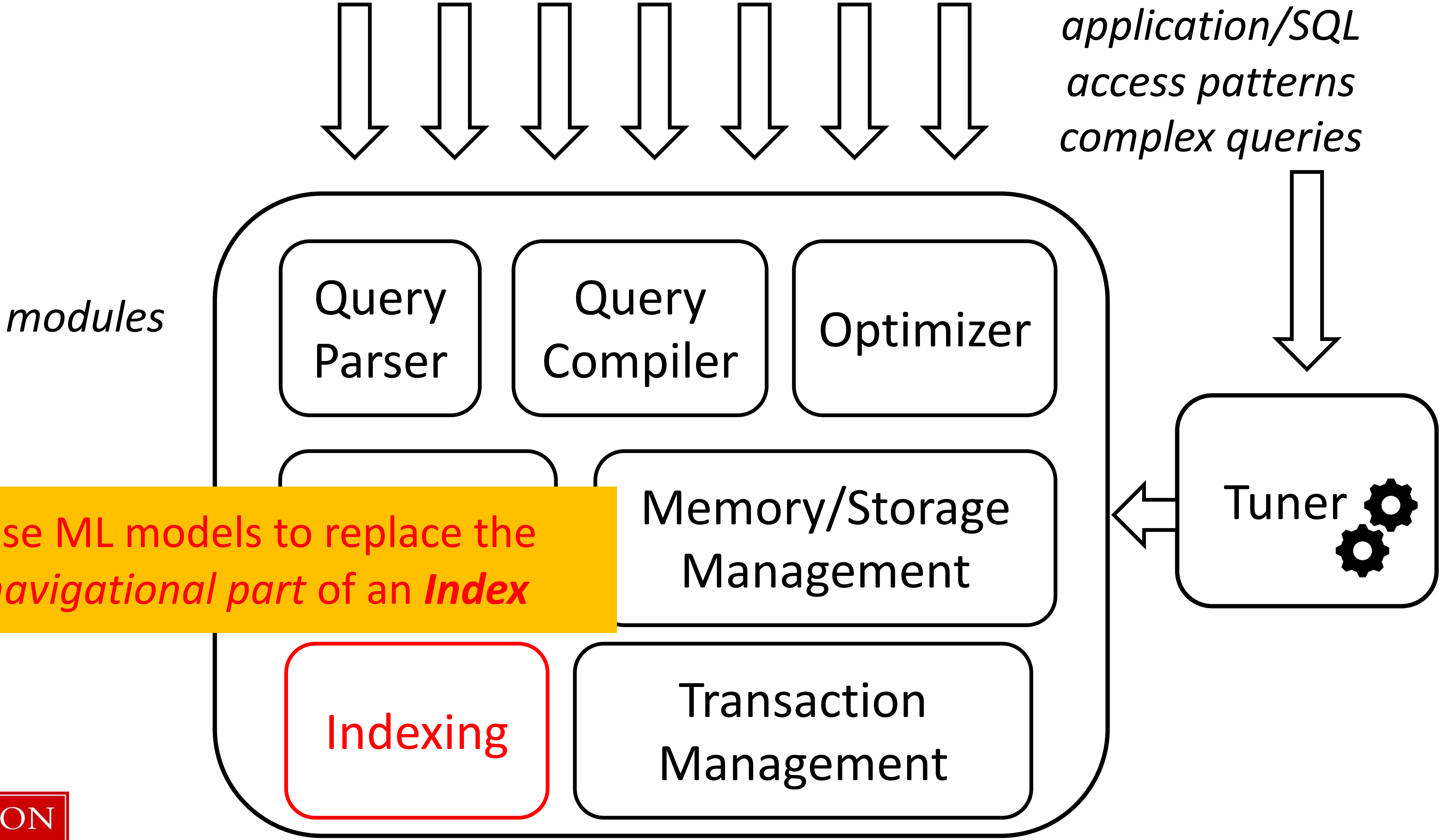

Use ML models to replace the *navigational part* of an ***Index***

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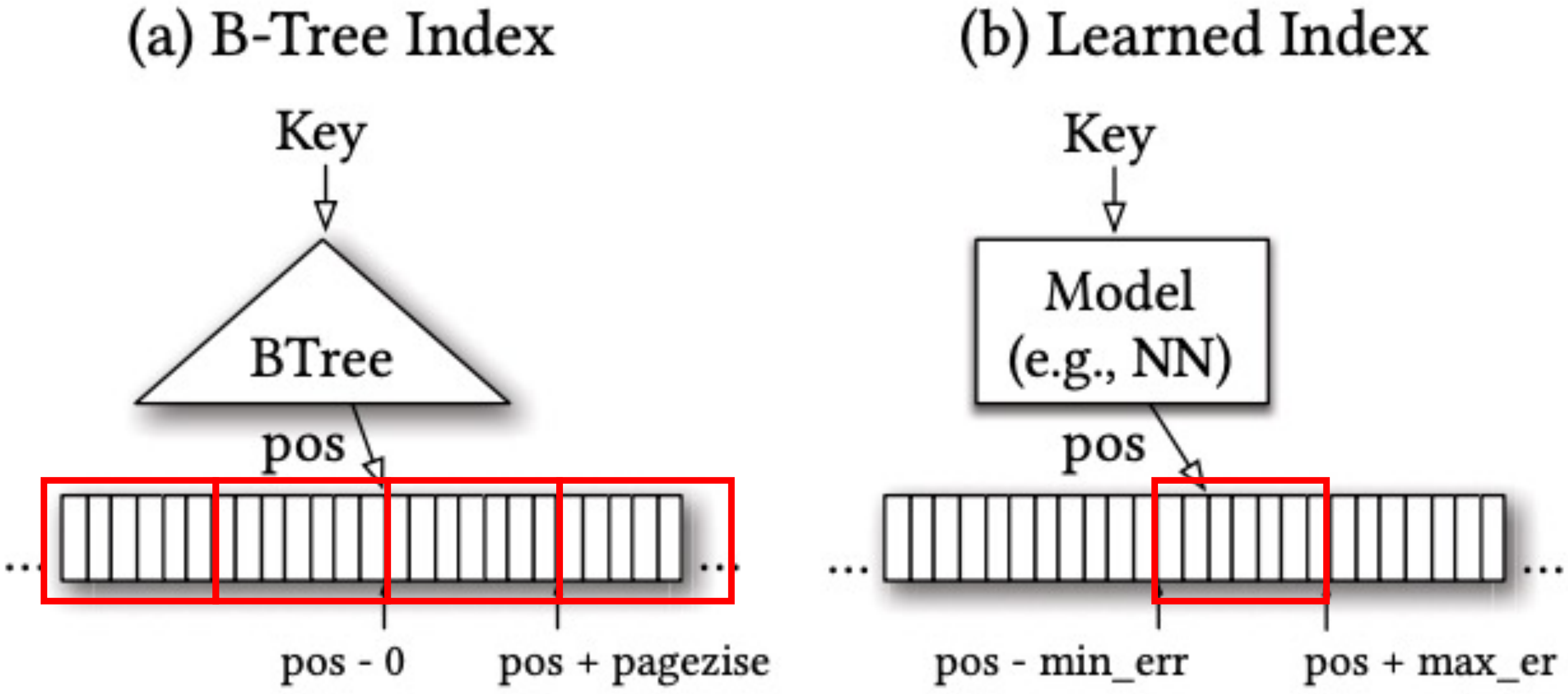
B-Trees vs. Learned Indexes



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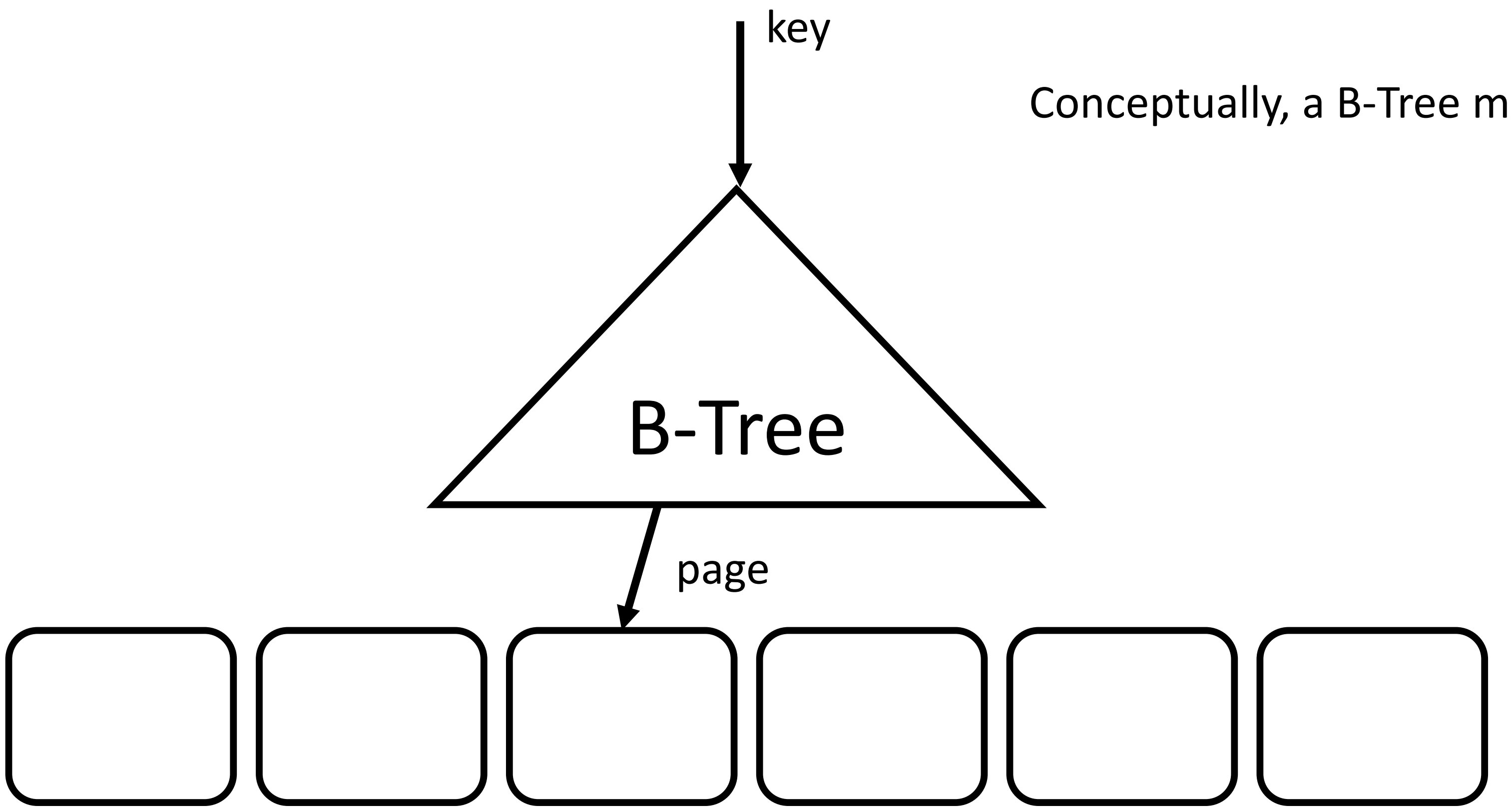
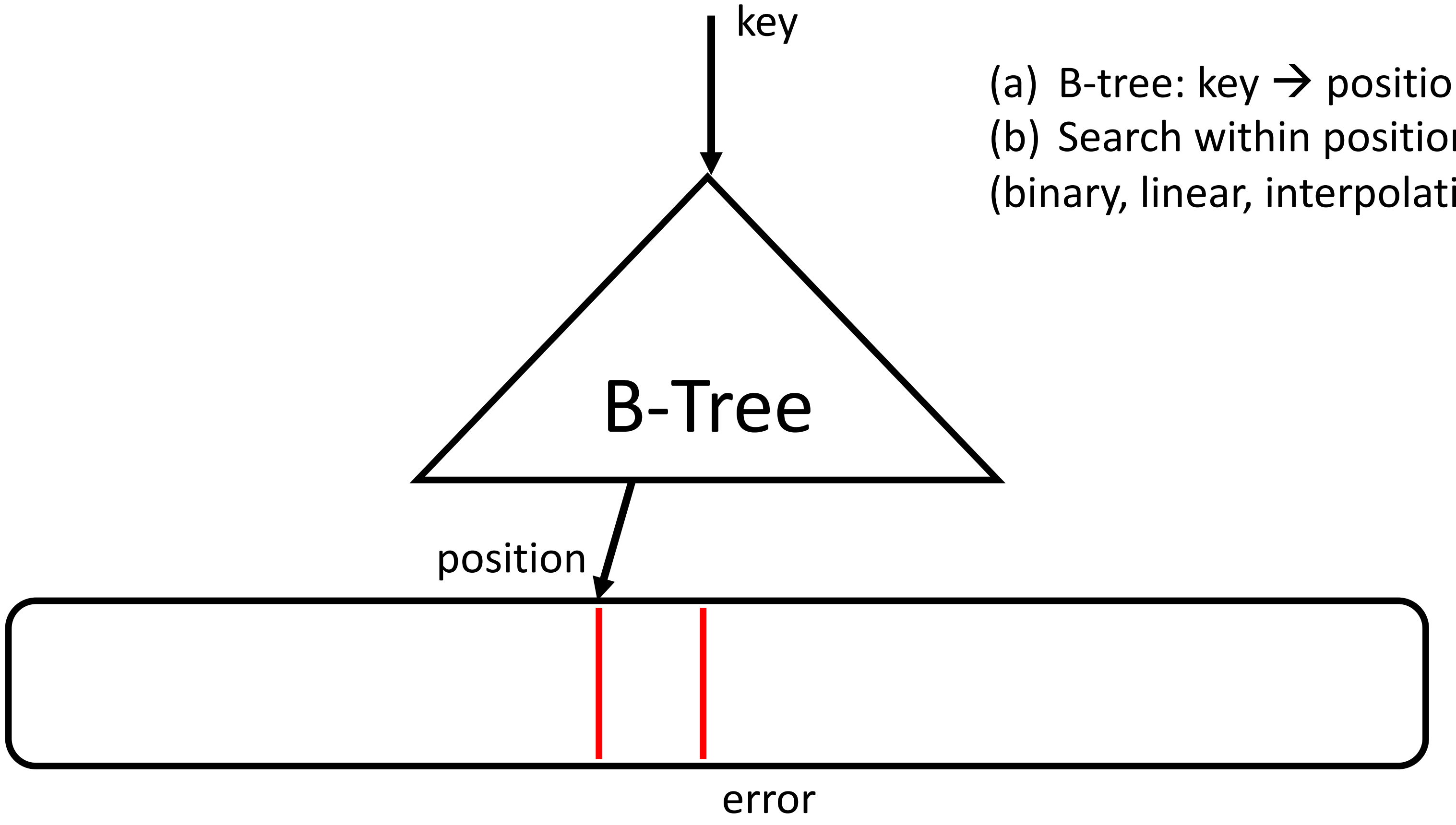
What is the difference?



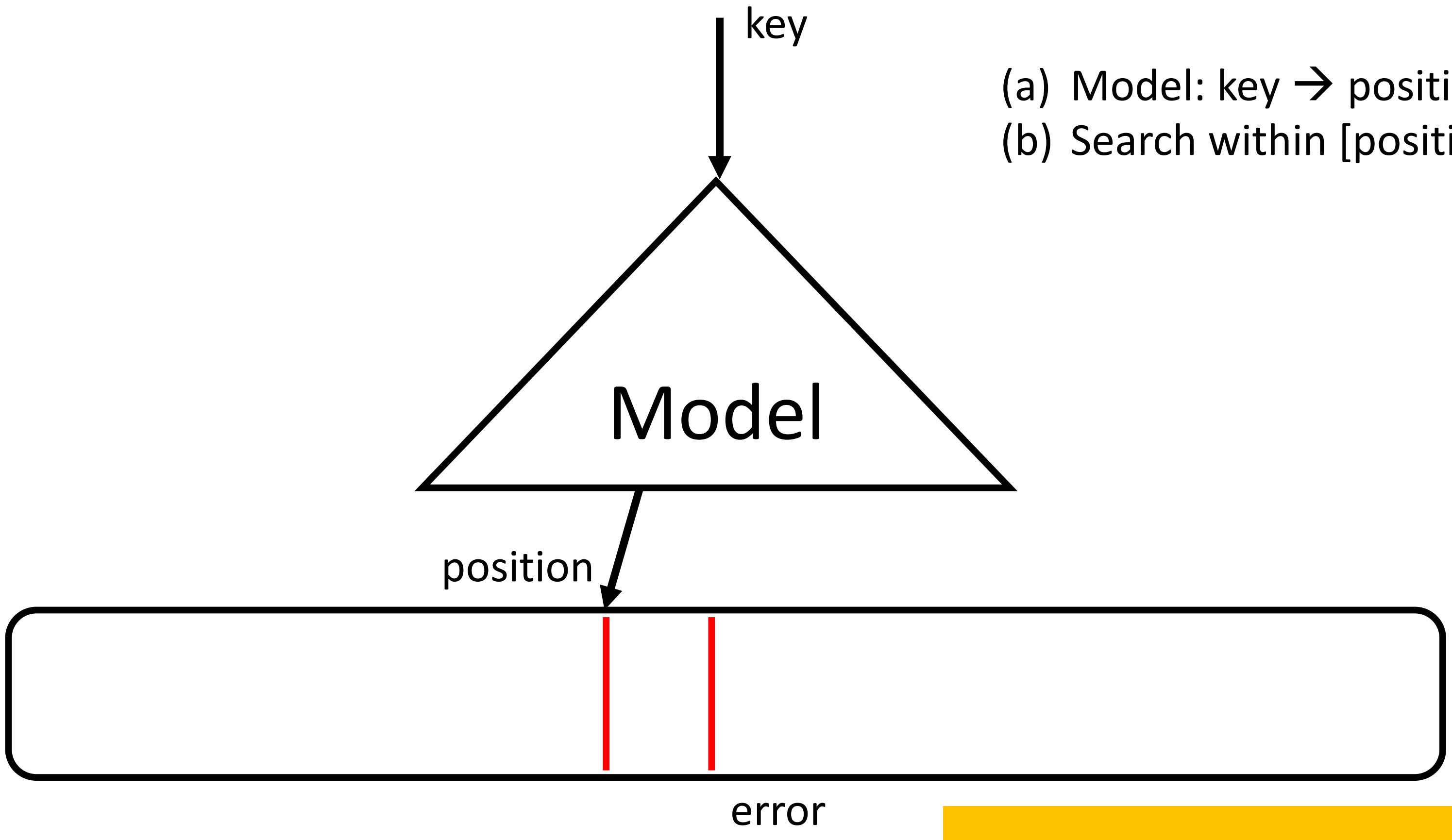
Conceptually, a B-Tree maps a key to a location (page)

Alternative view: data is sorted



(a) B-tree: key → position
(b) Search within position, position+error
(binary, linear, interpolation, exponential search)

A B-Tree is a Model



(a) Model: key → position estimate
(b) Search within [position-error, position+error]

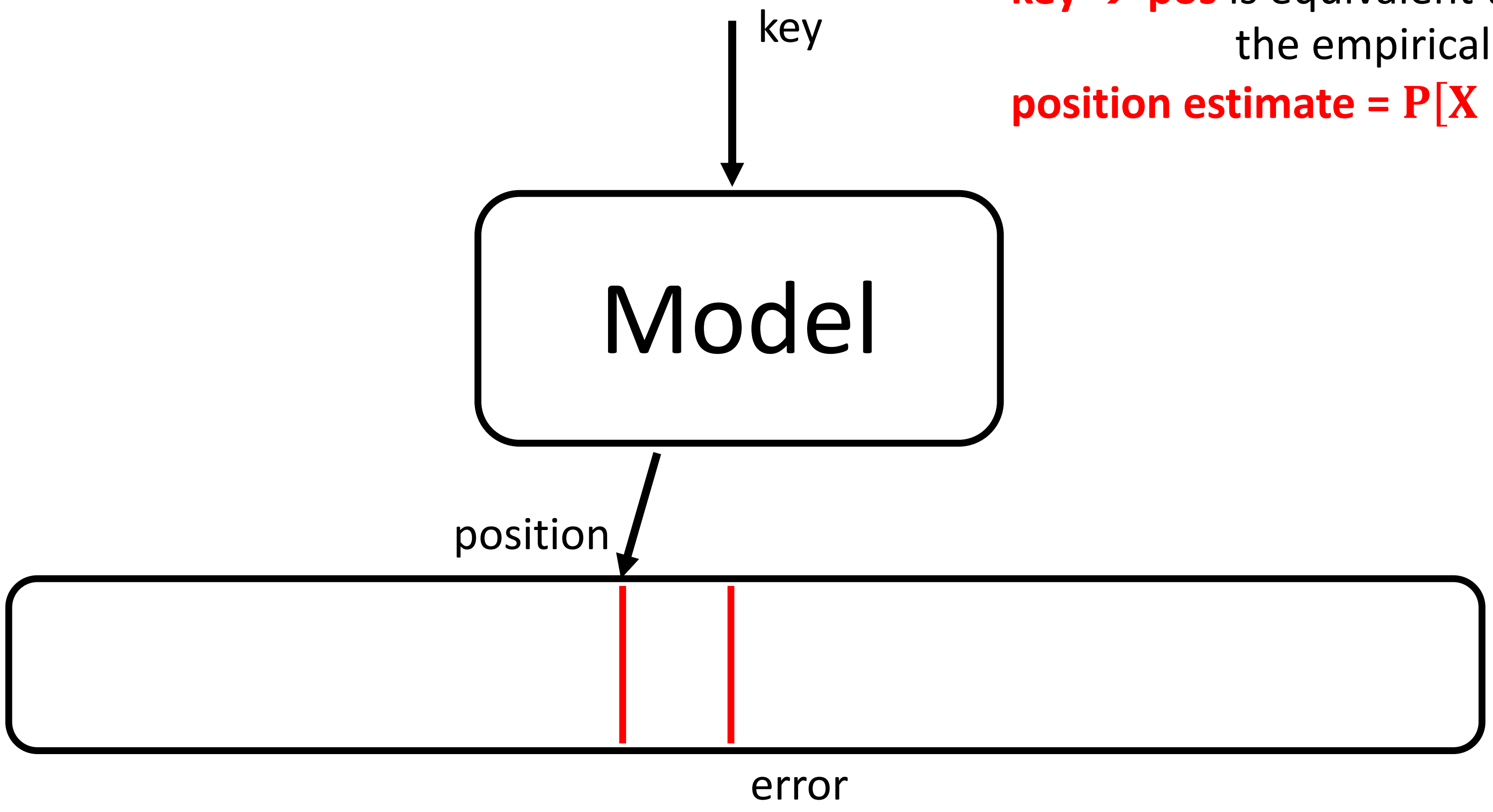
A B-Tree is already a model!

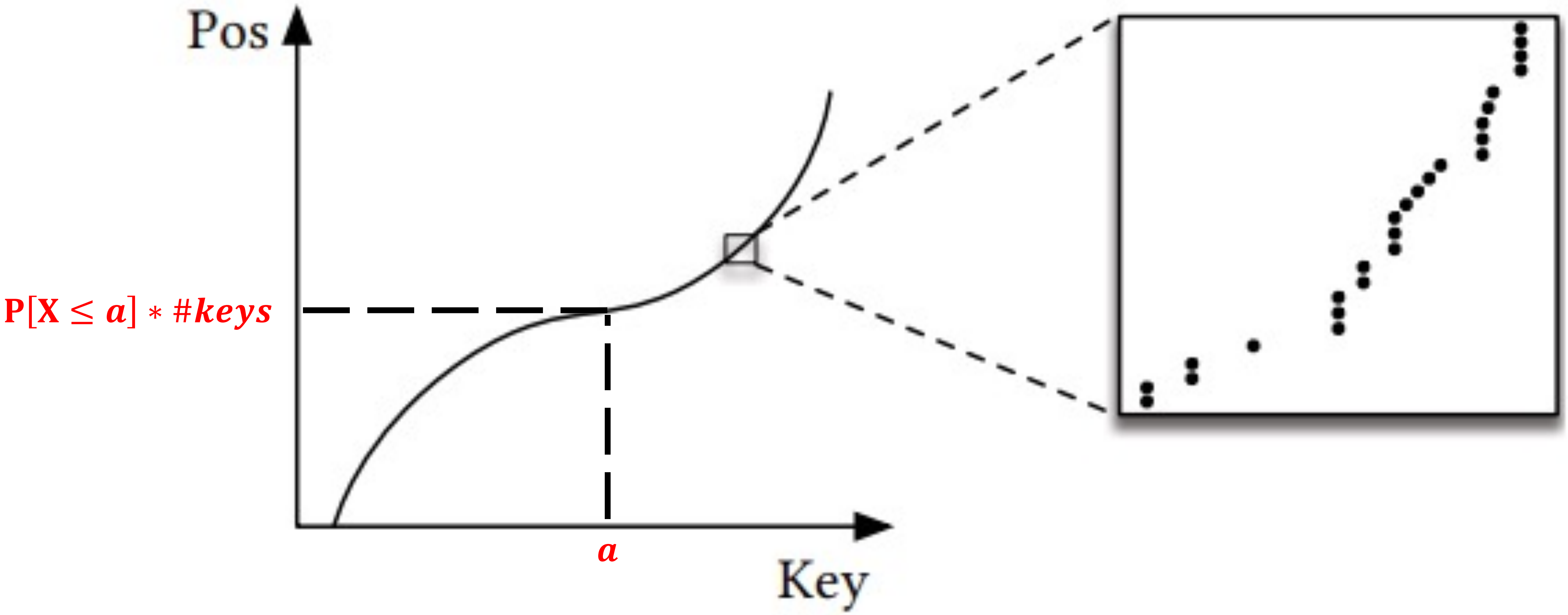
A B-Tree is a Model

A form of regression model

key → pos is equivalent to modeling
the empirical CDF of the data

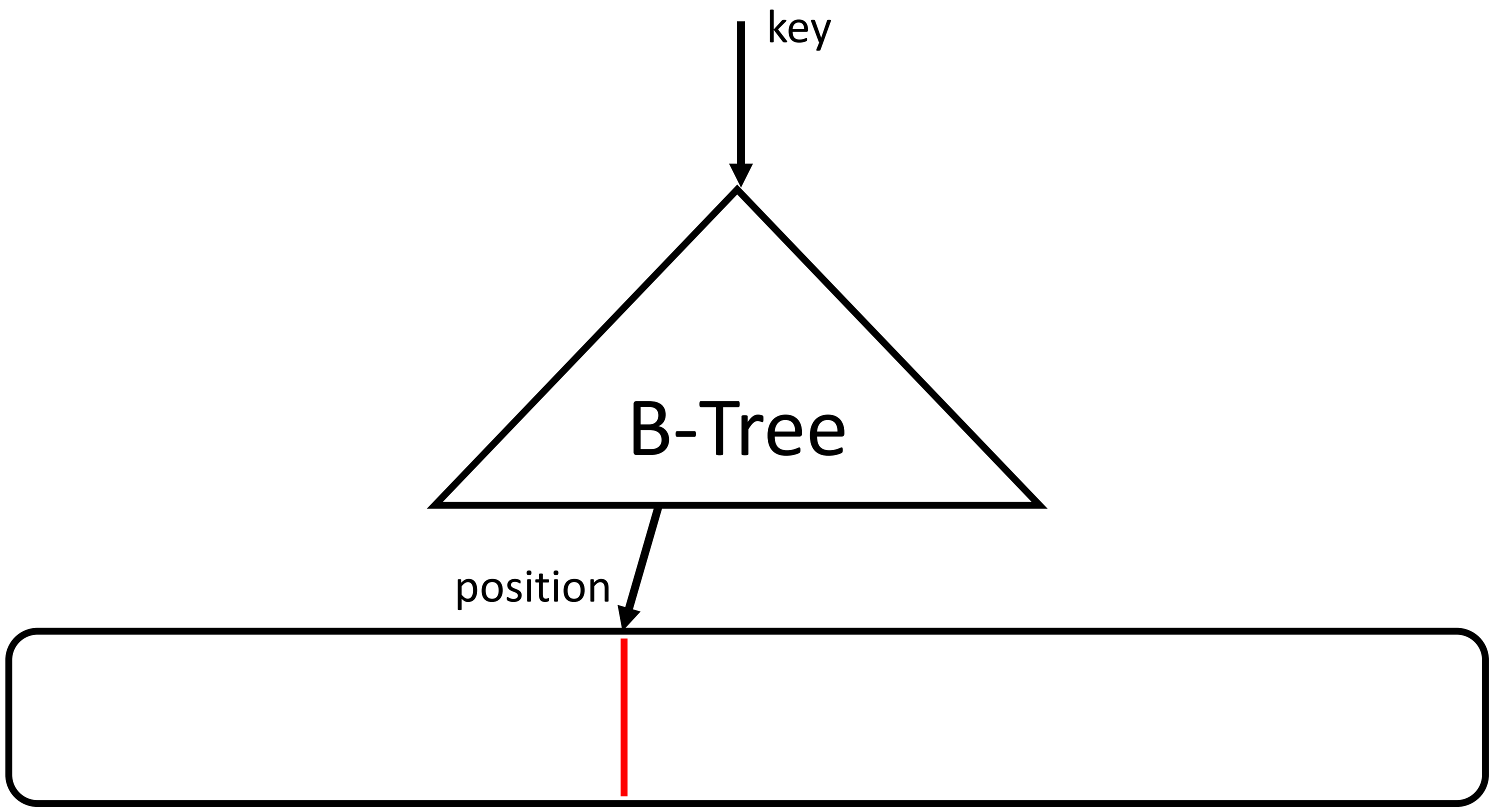
position estimate = $\mathbf{P[X \leq \mathit{key}] * \#\mathit{keys}}$





Pos
$\mathrm{P}[X \leq a] * \#keys$
a
Key

B-Trees are regression trees



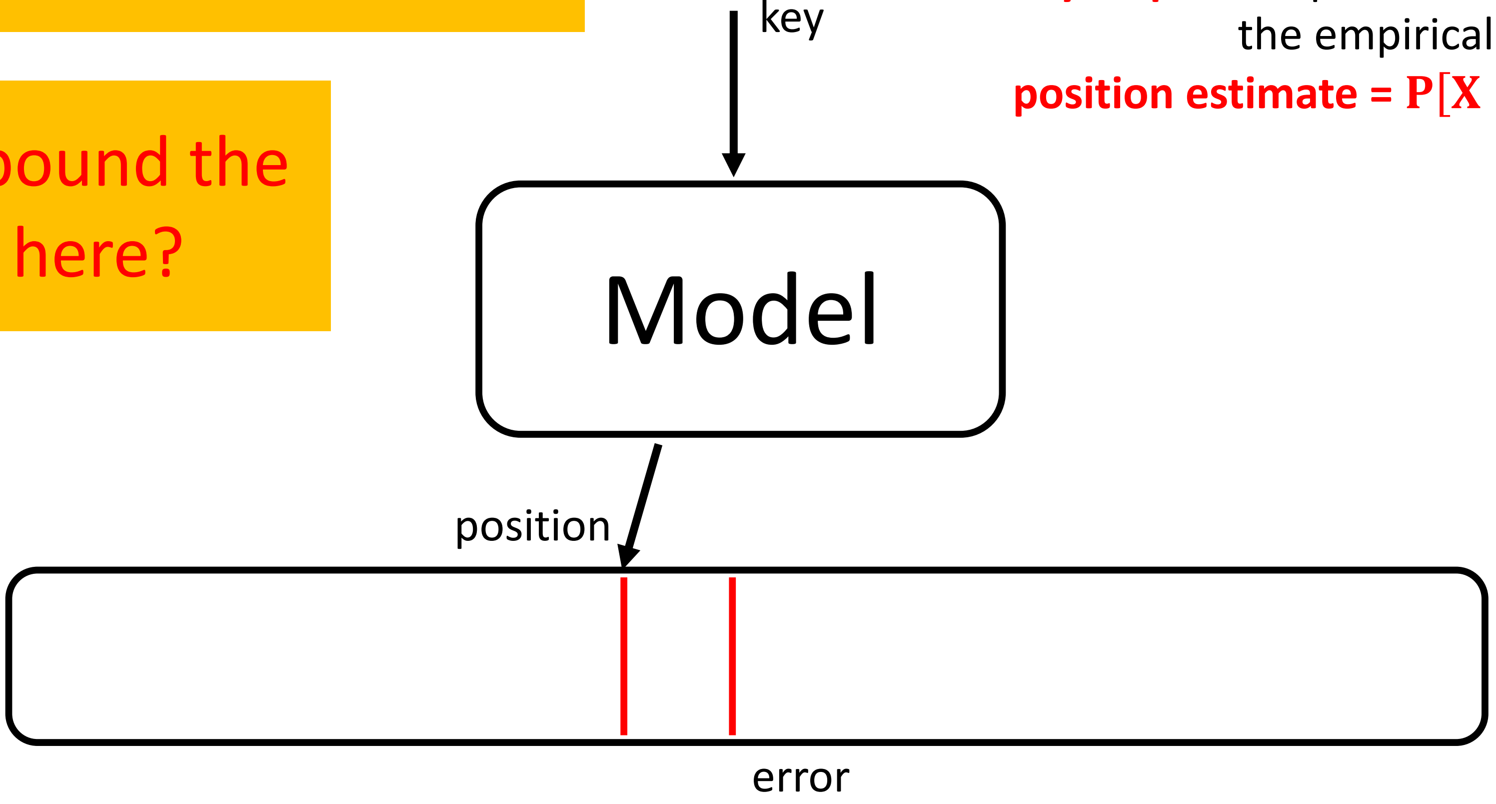
B-Trees is ***already*** a form of a learned index

What does this mean?

Learned Indexes

B-Trees have bounded error

Can we bound the error here?



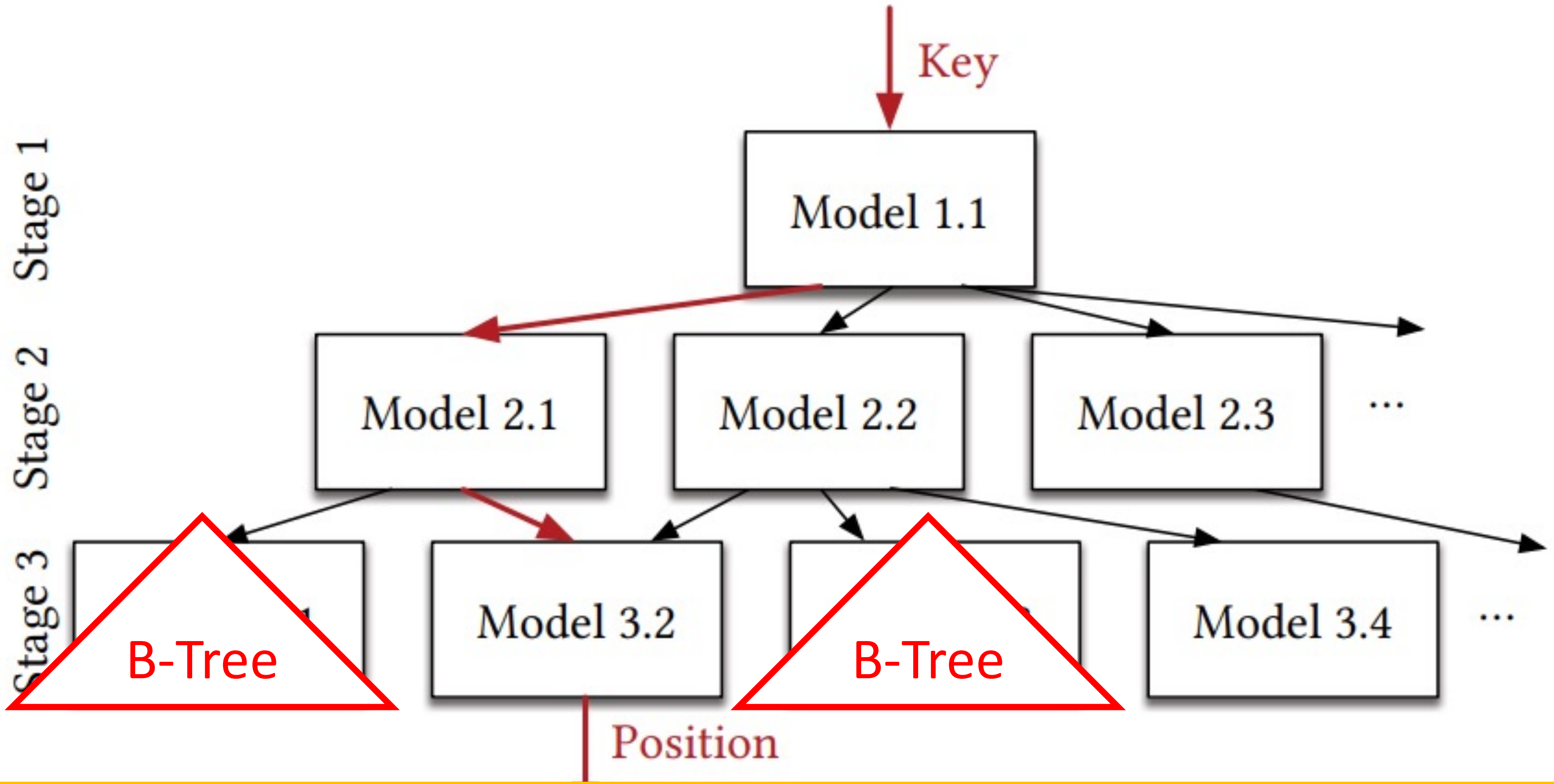
A form of regression model

key → pos is equivalent to modeling the empirical CDF of the data

position estimate = $\mathbf{P[X \leq \mathit{key}] * \#\mathit{keys}}$

What is the problem if we use an arbitrary model?

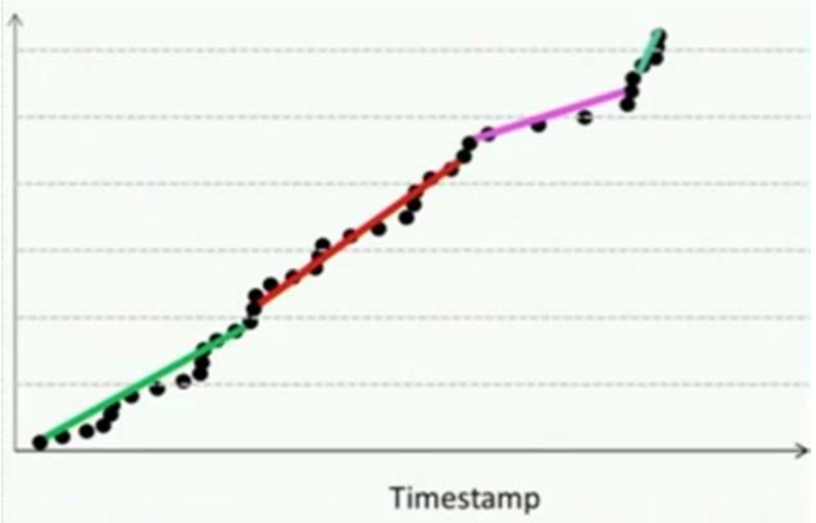
Last-mile indexing



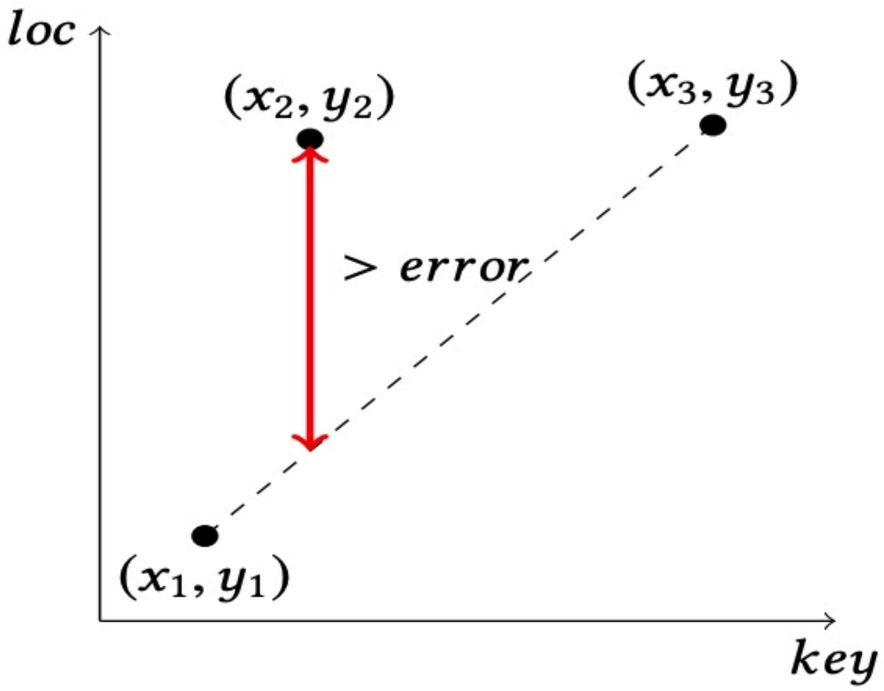
Some models can be replaced sub-B-Trees

Every level provides gain in accuracy

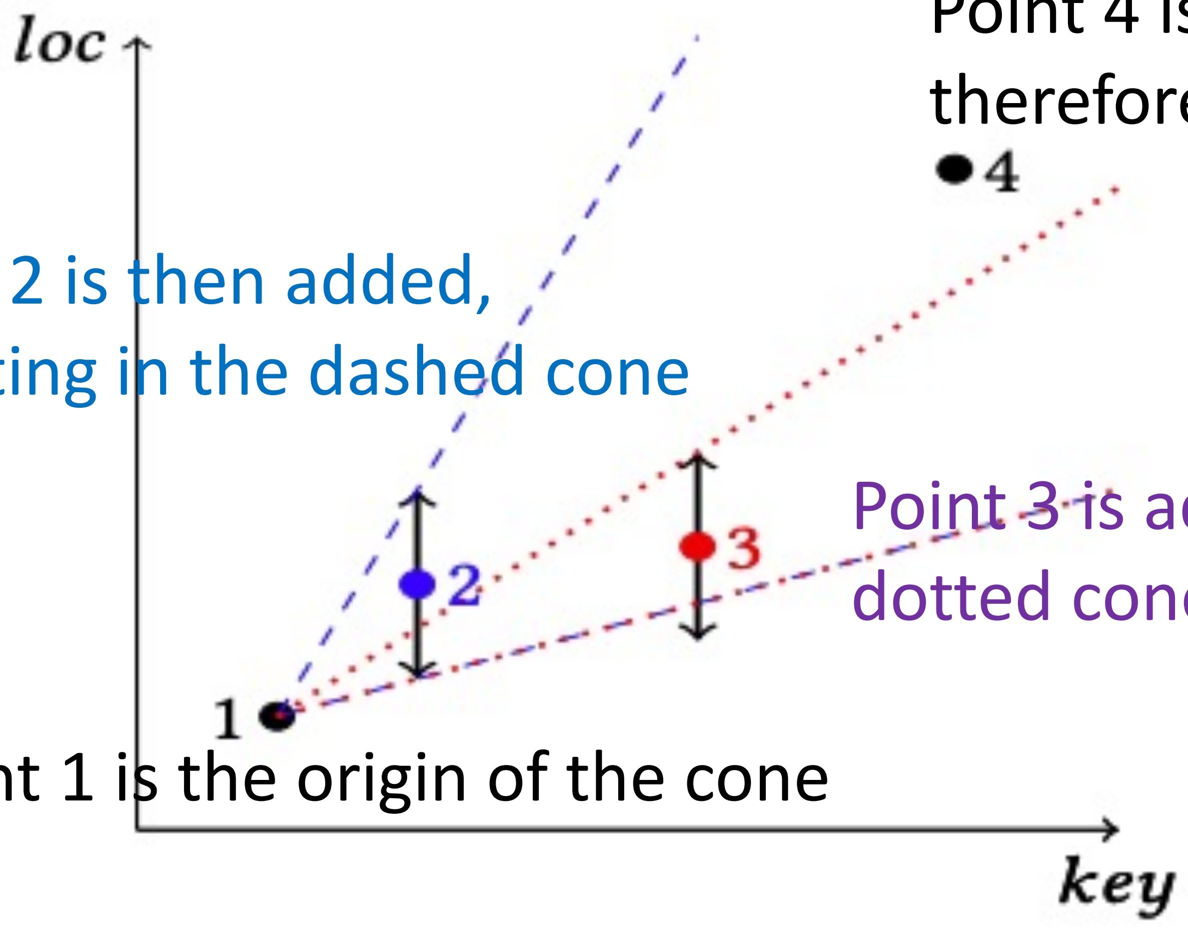
Use case: FITing-Tree



Piece-wise linear approximation



A segment from (x_1,y_1) to (x_3,y_3) is **not valid** if (x_2,y_2) is further than ***error*** from the interpolated line.

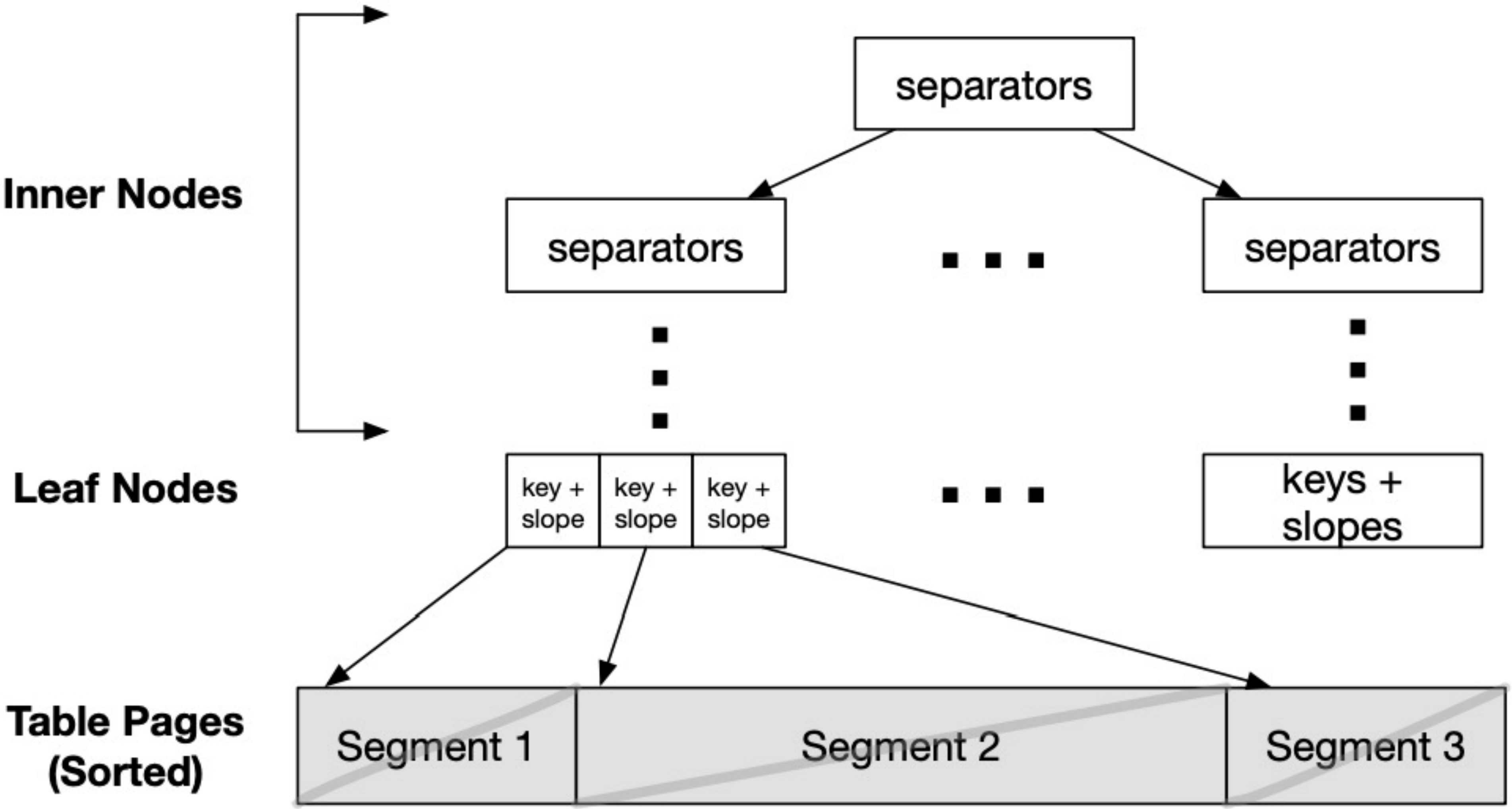


Point 4 is outside the dotted cone and therefore starts a new segment

Point 2 is then added, resulting in the dashed cone

Point 3 is added next, yielding in the dotted cone

Point 1 is the origin of the cone



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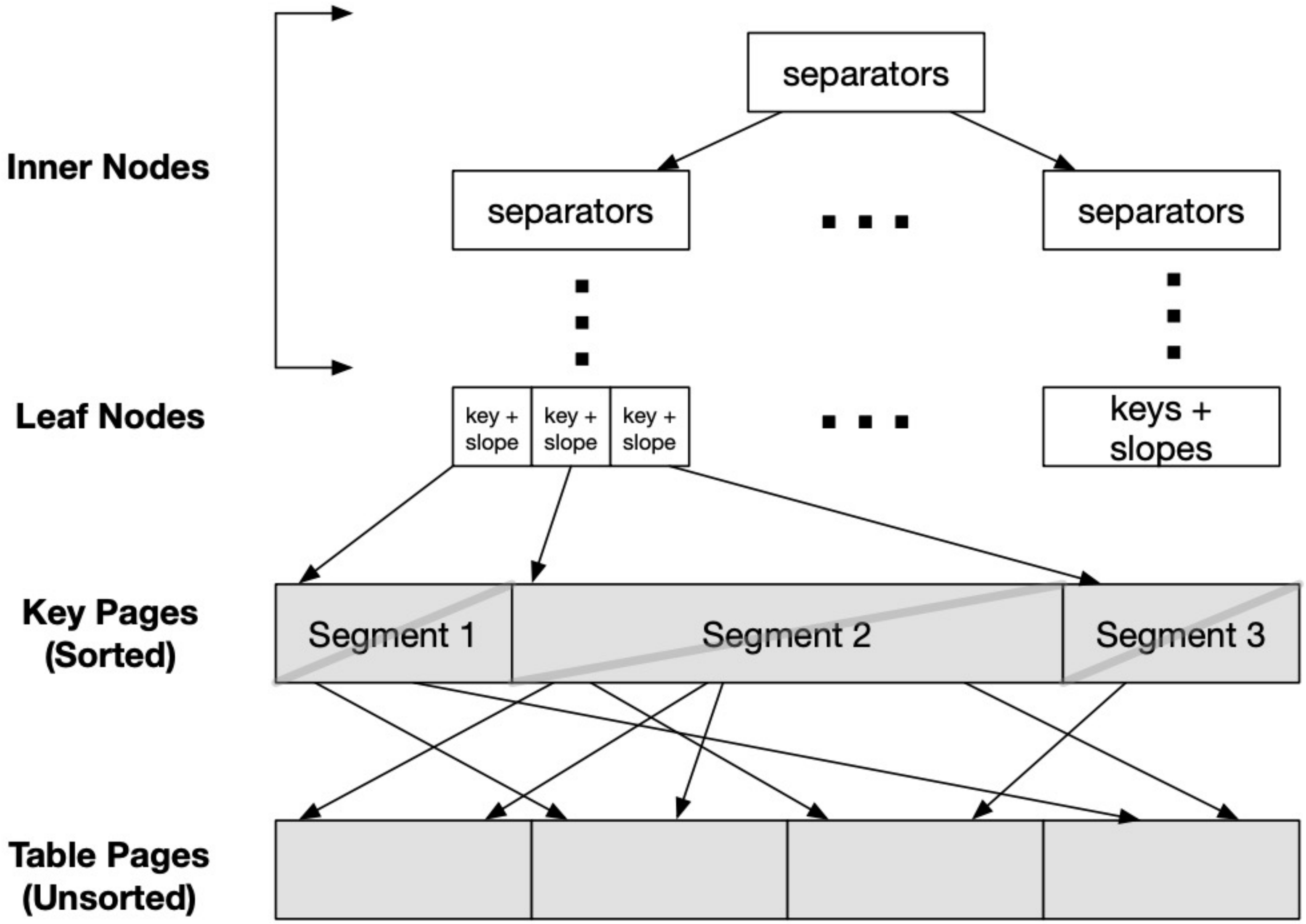
What if base data is not sorted?

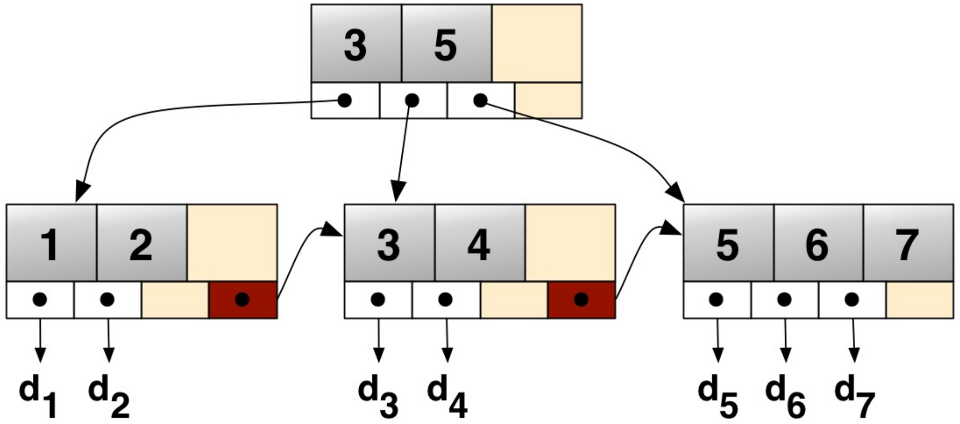


Need to materialize sorted data

What about updates and learned indexes?

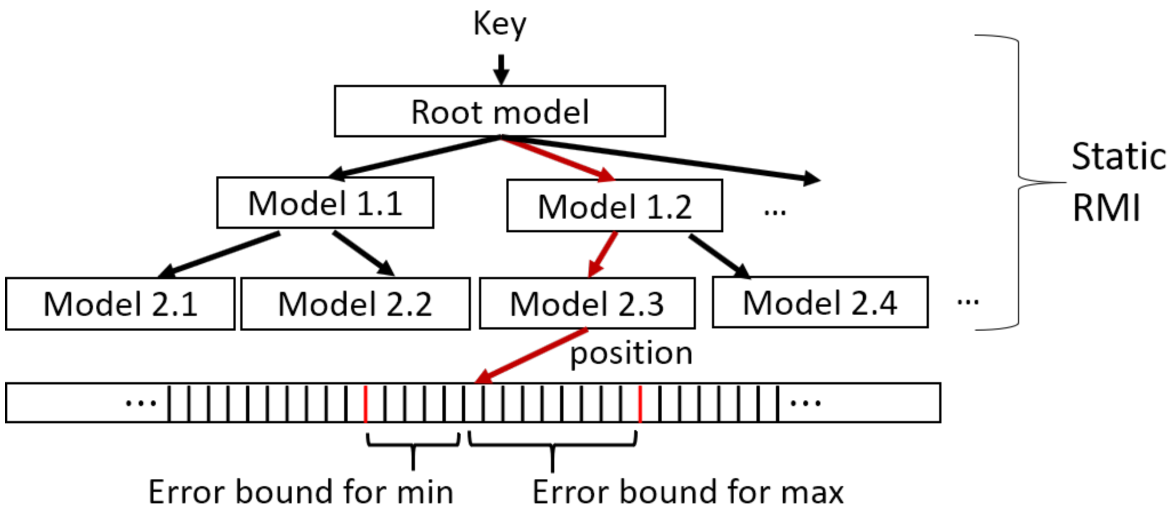
B+ Tree

- Traverses tree using comparisons
- Supports OLTP-style mixed workloads
  - Point lookups, range queries
  - Inserts, updates, deletes



Learned Index (Kraska et al., 2018)

- Traverses tree using computations (models)
- Supports point lookups and range queries
- Advantages: 3X faster reads, 10X smaller size
- Limitation: does not support writes



ALEX goals

	B+ Tree	Learned Index	ALEX
Lookup time	Slow	Fast	Faster
Insert time	Fast	Not Supported	Fast
Space usage	High	Low	Low

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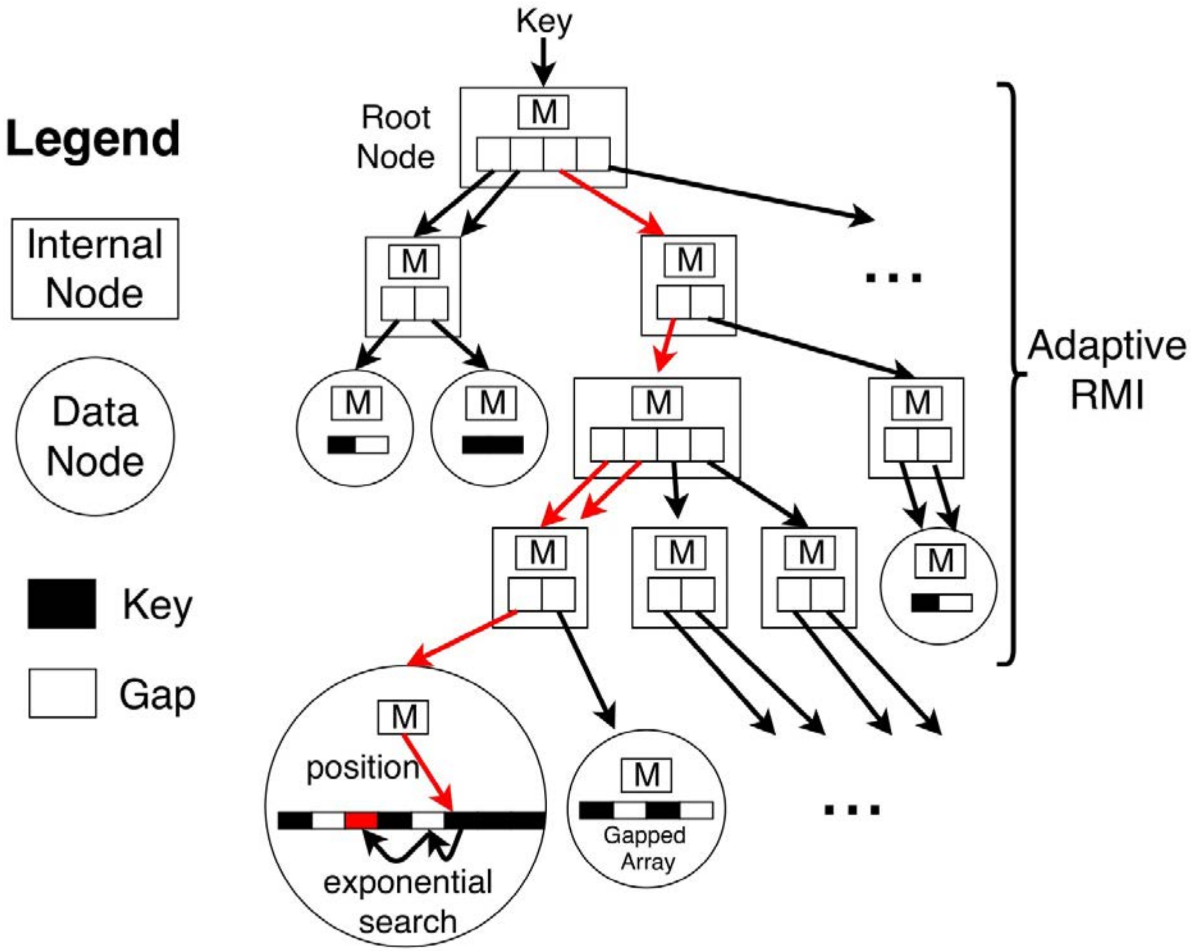
(every row should be read independently)

ALEX design overview

- Structure
  - Dynamic tree structure
  - Each node contains a linear model
    - At internal nodes, models select the node at the next level
    - At data nodes, models predict the position of a key
- Core operations
  - Lookup
    - Use RMI to predict location of key in a data node
    - Do local search to correct for prediction error
  - Insert
    - Do a lookup to find the insert position
    - Insert the new key/value (might require shifting)
- Current design constraints
  - In memory
  - Numeric data types
  - Single threaded



ALEX Core Ideas

	Faster Reads	Faster Writes	Adaptiveness
1. Gapped Array		✓	
2. Model-based Inserts	✓		
3. Exponential Search	✓		
4. Adaptive Tree Structure	✓	✓	✓

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1. Gapped Array

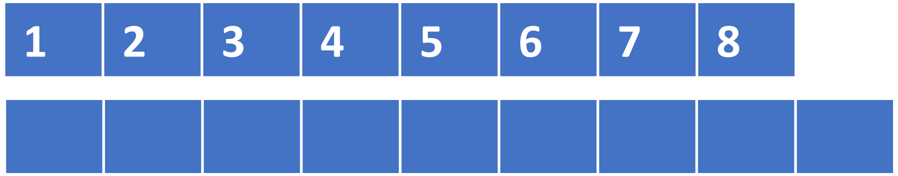
How should data be stored in data nodes?

1. Gapped Array

Dense Array	1	2	3	4	5	6	7	8

1. Gapped Array

Dense Array



1. Gapped Array

Dense Array

1	2	3	4	5	6	7	8	
	1	2	3	4	5	6	7	8

1. Gapped Array

Dense Array

1	2	3	4	5	6	7	8

0	1	2	3	4	5	6	7	8

1. Gapped Array

Dense Array

0	1	2	3	4	5	6	7	8

1. Gapped Array

Insertion Time

Dense Array

0	1	2	3	4	5	6	7	8

$O(n)$

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1. Gapped Array

Insertion Time

Dense Array

0	1	2	3	4	5	6	7	8

$O(n)$

B+ Tree Node

1	2	3	4	5	6	7	8				

1. Gapped Array

Insertion Time

Dense Array

0	1	2	3	4	5	6	7	8

$O(n)$

B+ Tree Node

	1	2	3	4	5	6	7	8			

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1. Gapped Array

Insertion Time

Dense Array

0	1	2	3	4	5	6	7	8

$O(n)$

B+ Tree Node

0	1	2	3	4	5	6	7	8			

1. Gapped Array

Insertion Time

Dense Array

$O(n)$

B+ Tree Node

$O(n)$

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1. Gapped Array

													Insertion Time
Dense Array	0	1	2	3	4	5	6	7	8				$O(n)$
B+ Tree Node	0	1	2	3	4	5	6	7	8				$O(n)$
Gapped Array	1	2		3	4		5	6		7	8		

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1. Gapped Array

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1. Gapped Array

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Dense Array	0	1	2	3	4	5	6	7	8				$O(n)$
B+ Tree Node	0	1	2	3	4	5	6	7	8				$O(n)$
Gapped Array	0	1	2	3	4		5	6		7	8		$O(\log n)$

1. Gapped Array

													Insertion Time
Dense Array	0	1	2	3	4	5	6	7	8				$O(n)$
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Storing data in Gapped Arrays achieves inserts using fewer shifts, leading to faster writes

1. Gapped Array

													Insertion Time
Dense Array	0	1	2	3	4	5	6	7	8				$O(n)$
B+ Tree Node	0	1	2	3	4	5	6	7	8				$O(n)$
Gapped Array	0	1	2	3	4	5	5	6	7	7	8	S	$O(\log n)$

Storing data in Gapped Arrays achieves inserts using fewer shifts, leading to faster writes

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2. Model-based Inserts

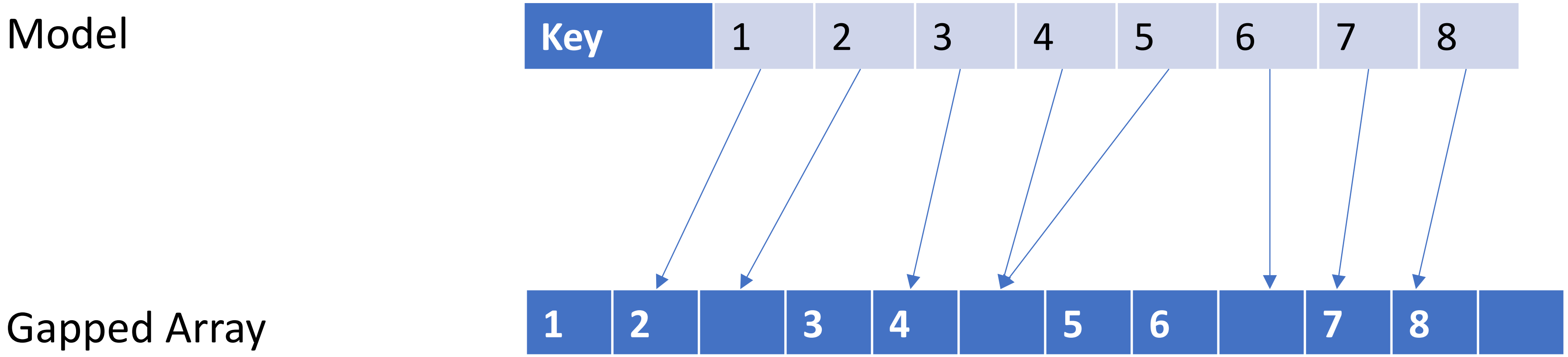
Where do we put gaps in the Gapped Array?

2. Model-based Inserts

Gapped Array

1	2		3	4		5	6		7	8	

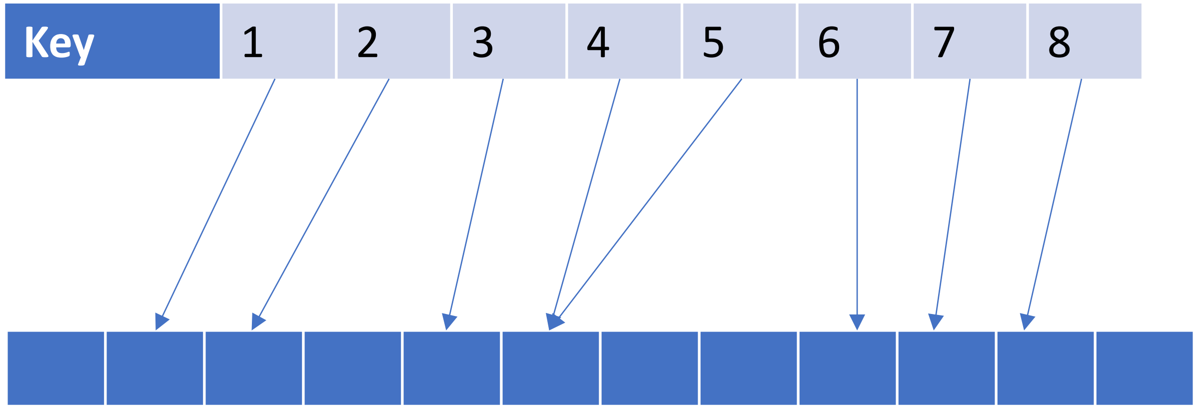
2. Model-based Inserts



2. Model-based Inserts

Model

Gapped Array



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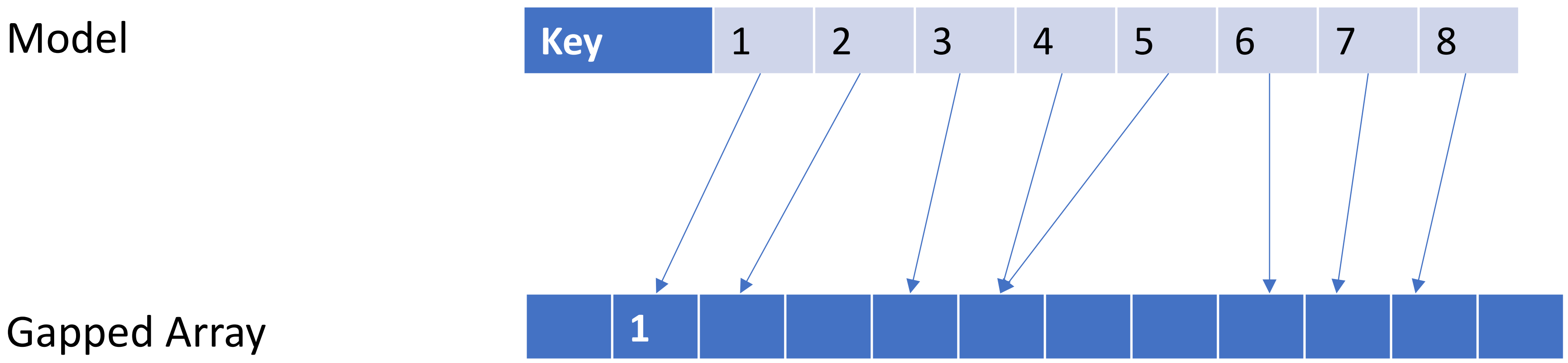
2. Model-based Inserts



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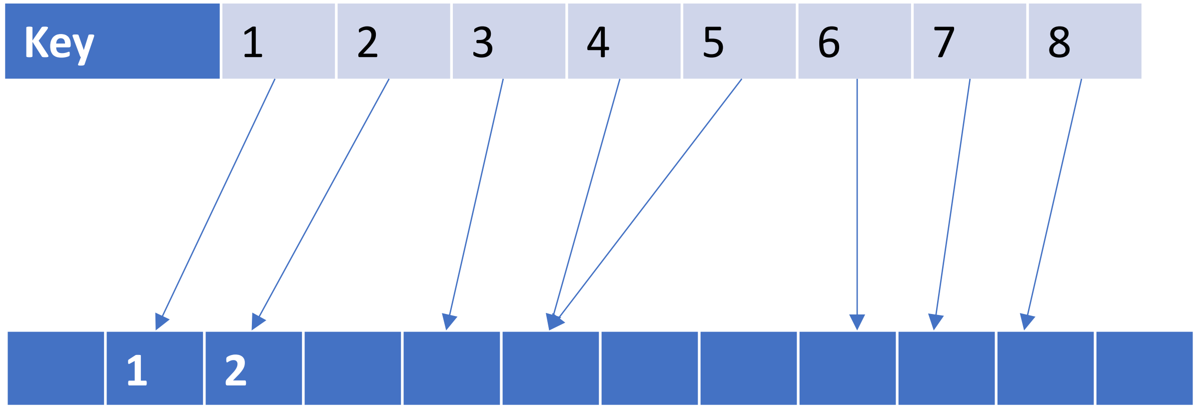
2. Model-based Inserts

Model

Gapped Array



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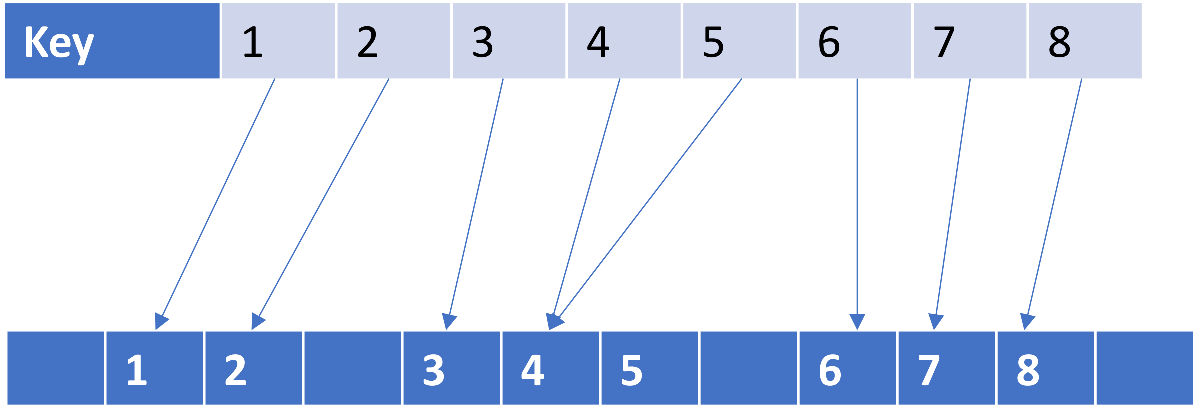
2. Model-based Inserts

Model

Gapped Array



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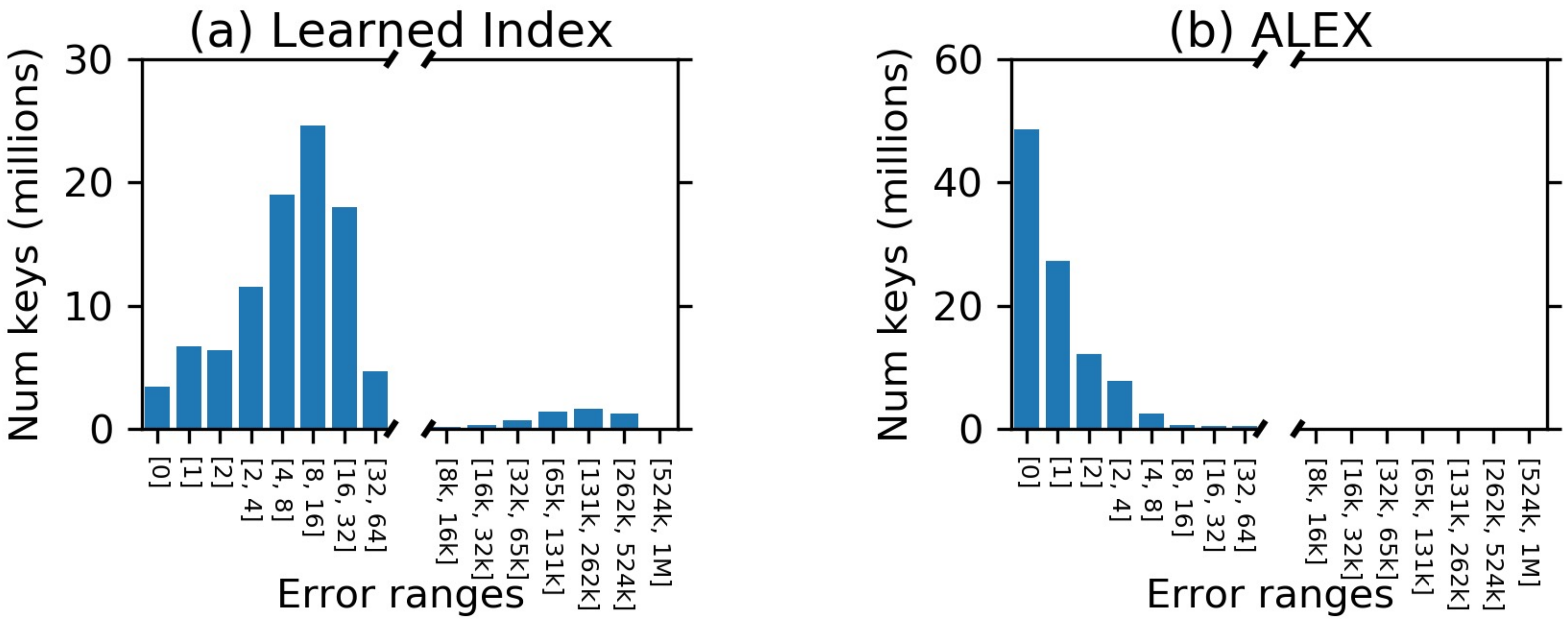
2. Model-based Inserts



Model-based inserts achieve lower prediction error, leading to faster reads

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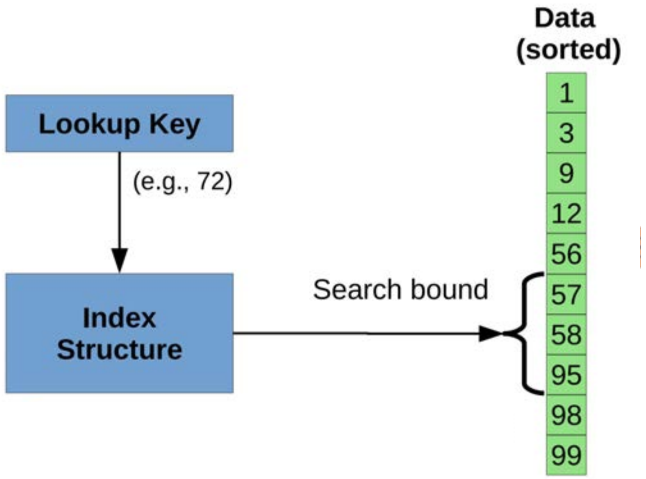
3. Exponential Search



Can we do better than binary search?

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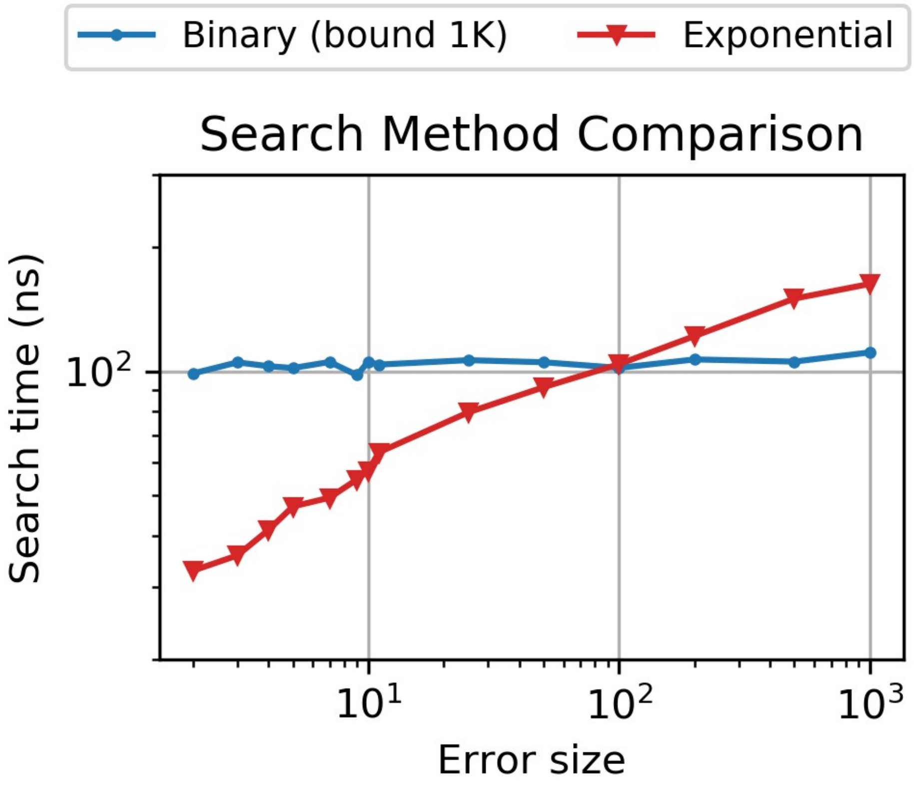
3. Exponential Search



Model errors are low, so exponential search is faster than binary search

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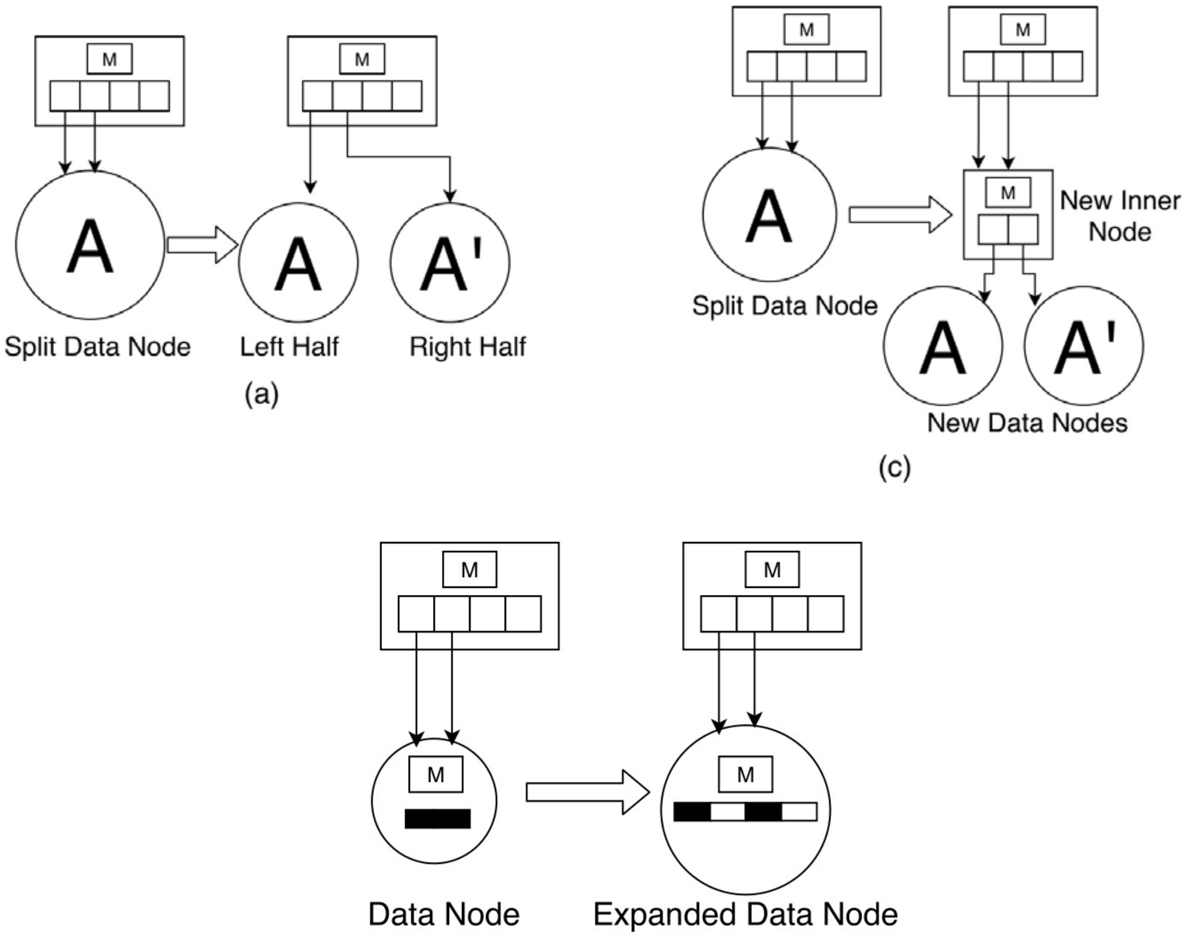
4. Adaptive Structure

What happens if data nodes become full?

What happens if models become inaccurate?

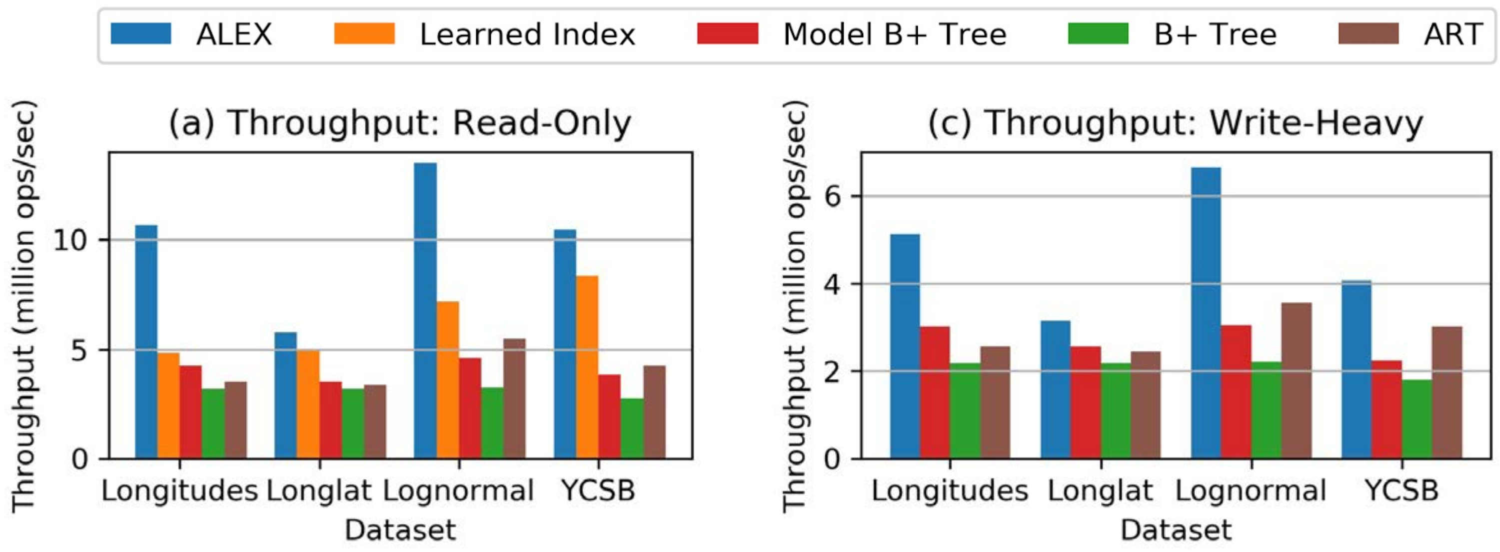
4. Adaptive Structure

- Flexible tree structure
    - Split nodes sideways
    - Split nodes downwards
    - Expand nodes
    - Merge nodes, contract nodes
- Key idea: all decisions are made to maximize performance
    - Use cost model of query runtime
    - No hand-tuning
    - Robust to data and workload shifts



Results

- High-level results
  - Fast reads
  - Fast writes

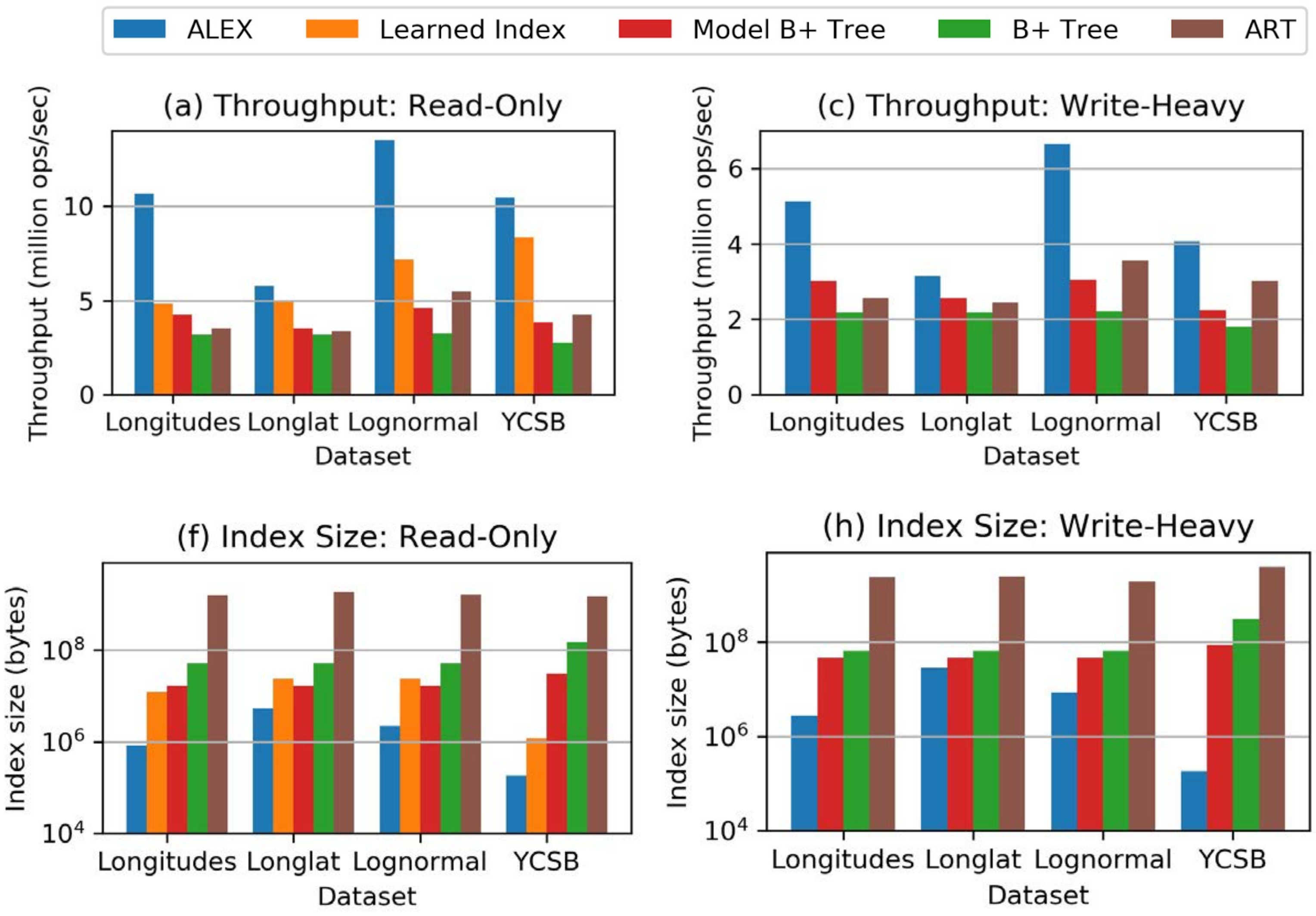


~4x faster than B+ Tree
~2x faster than Learned Index

~2-3x faster than B+ Tree

Results

- High-level results
  - Fast reads
  - Fast writes
  - Smaller index size
- Other results
  - Efficient bulk loading
  - Scales
  - Robust to data and workload shift



~3 orders of magnitude less space for index

ALEX Summary

- Combines the best of B+ Tree and Learned Indexes
  - Supports OLTP-style mixed workloads
    - Point lookups, range queries
    - Inserts, updates, deletes
  - Up to 4X faster, 2000X smaller than B+ Tree
- Current research
  - String keys
  - Concurrency
  - Persistence

	Faster Reads	Faster Writes	Adaptiveness
Gapped Array		✓	
Model-based Inserts	✓		
Exponential Search	✓		
Adaptive Tree Structure	✓	✓	✓

github.com/microsoft/ALEX