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CS 561: Data Systems Architectures

class 11

Adaptive Radix Trees

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

Indexing is key to database performance

B⁺ Trees and **LSM-Trees** dominate disk-based indexes

Hash indexes and optimized search trees are common for in-memory

BUT

Hash indexes are unordered (no range queries)

Search trees are slower than Hash indexes for point queries

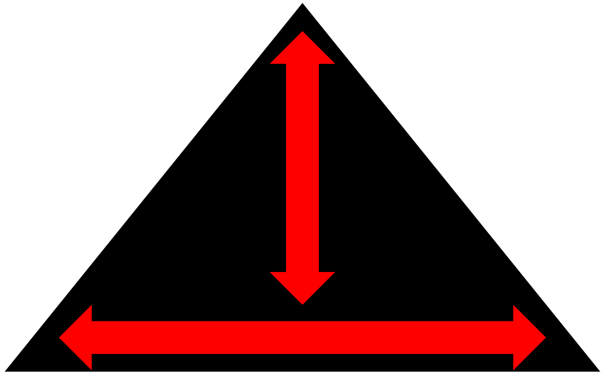
can we build a better compromise?

Increasing data size

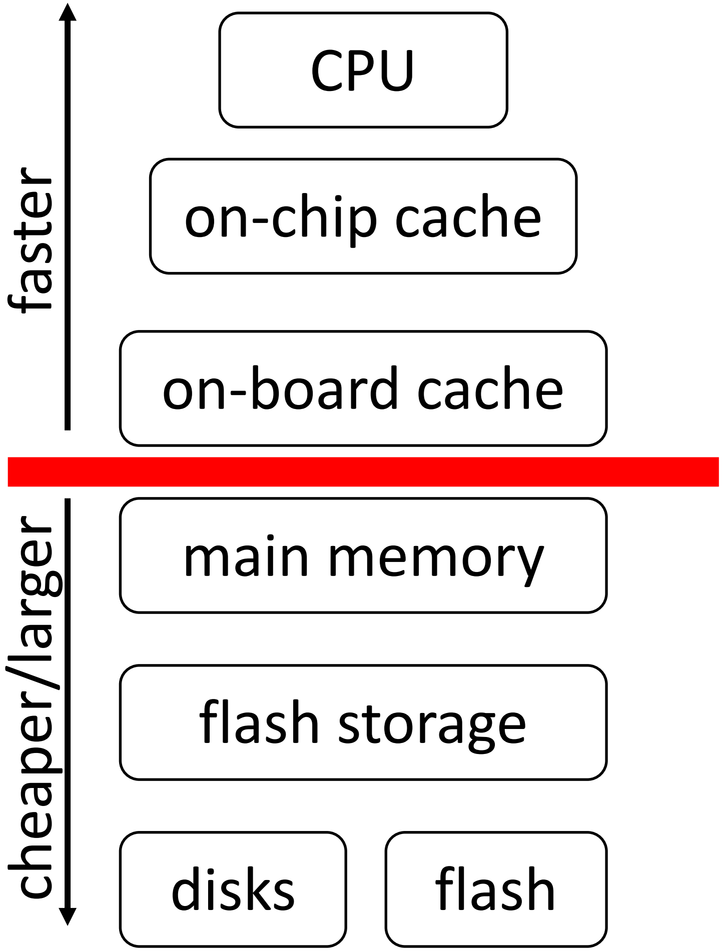
Search trees size (tree height and width) grows with data size!

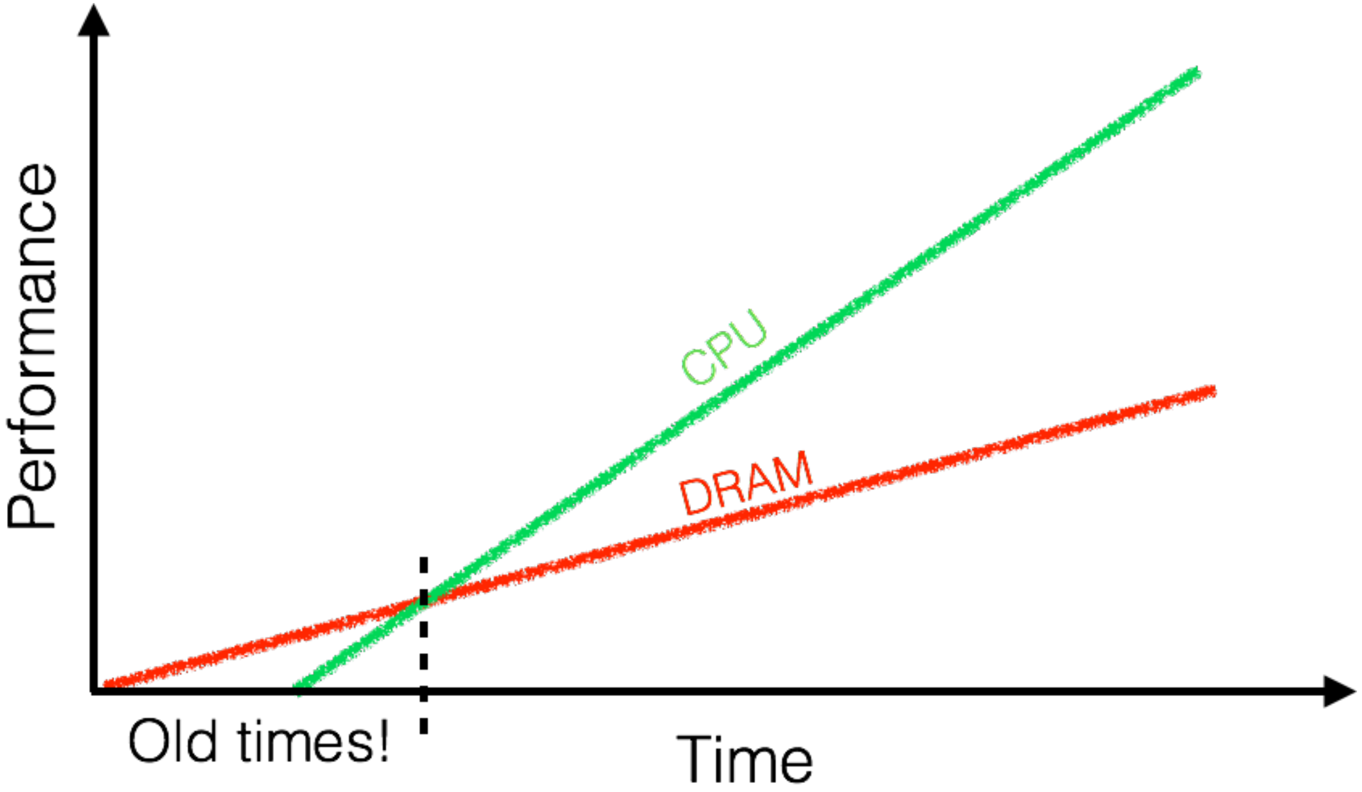
So, it quickly **does not fit** in cache or in memory

Why is that problem?



Reminder: Memory Wall





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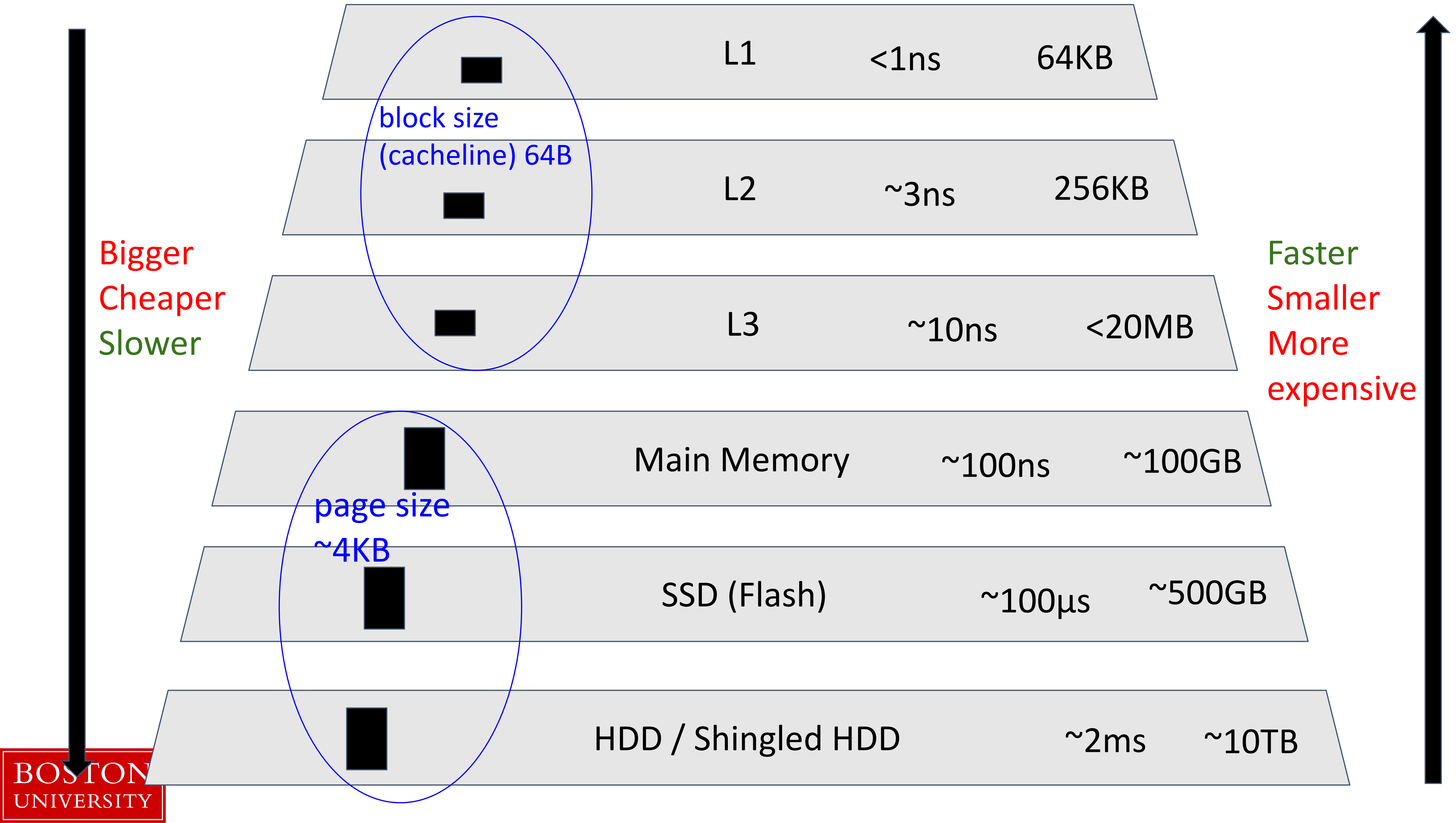
L1
<1ns
64KB
block size
(cacheline) 64B
L2
~3ns
256KB
Bigger
Cheaper
Slower
L3
~10ns
<20MB
Faster
Smaller
More
expensive
Main Memory
~100ns
~100GB
page size
~4KB
SSD (Flash)
~100µs
~500GB
HDD / Shingled HDD
~2ms
~10TB
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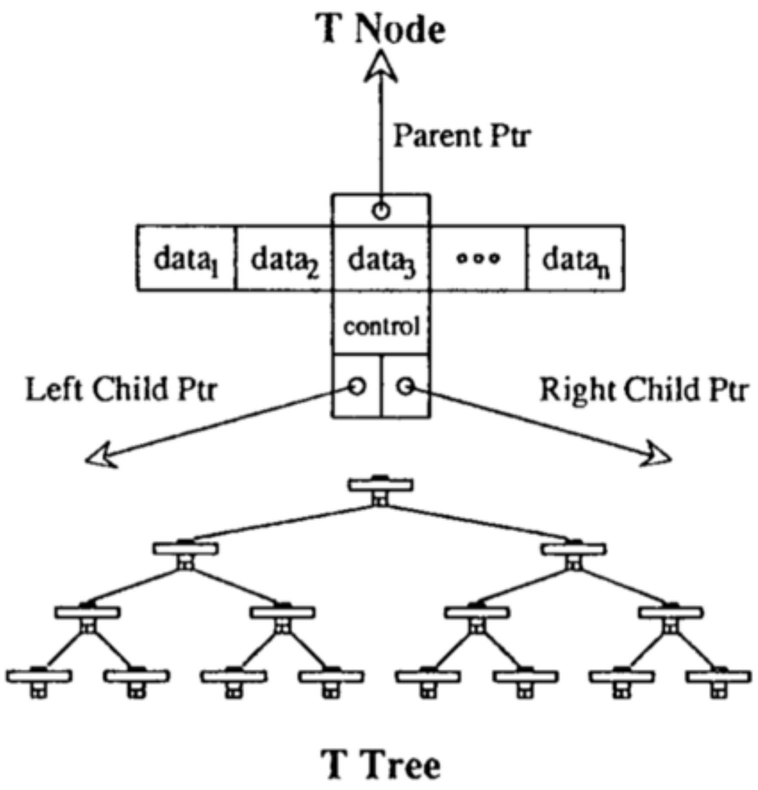
In-Memory Search Trees: T-Trees

Fat nodes (<u>cacheline</u> size) with **two** children

Developed in the 80s (still used in some systems!)

Unpredictable pointer chasing

Memory access **latency is not uniform**



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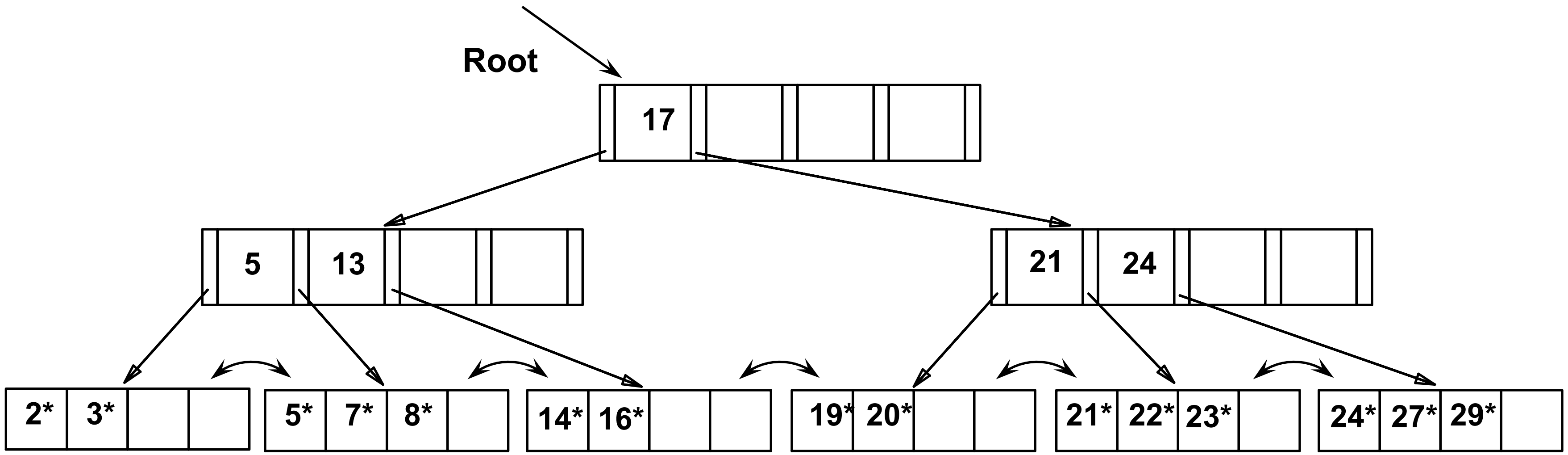
Are B+ Trees good for in-memory execution?

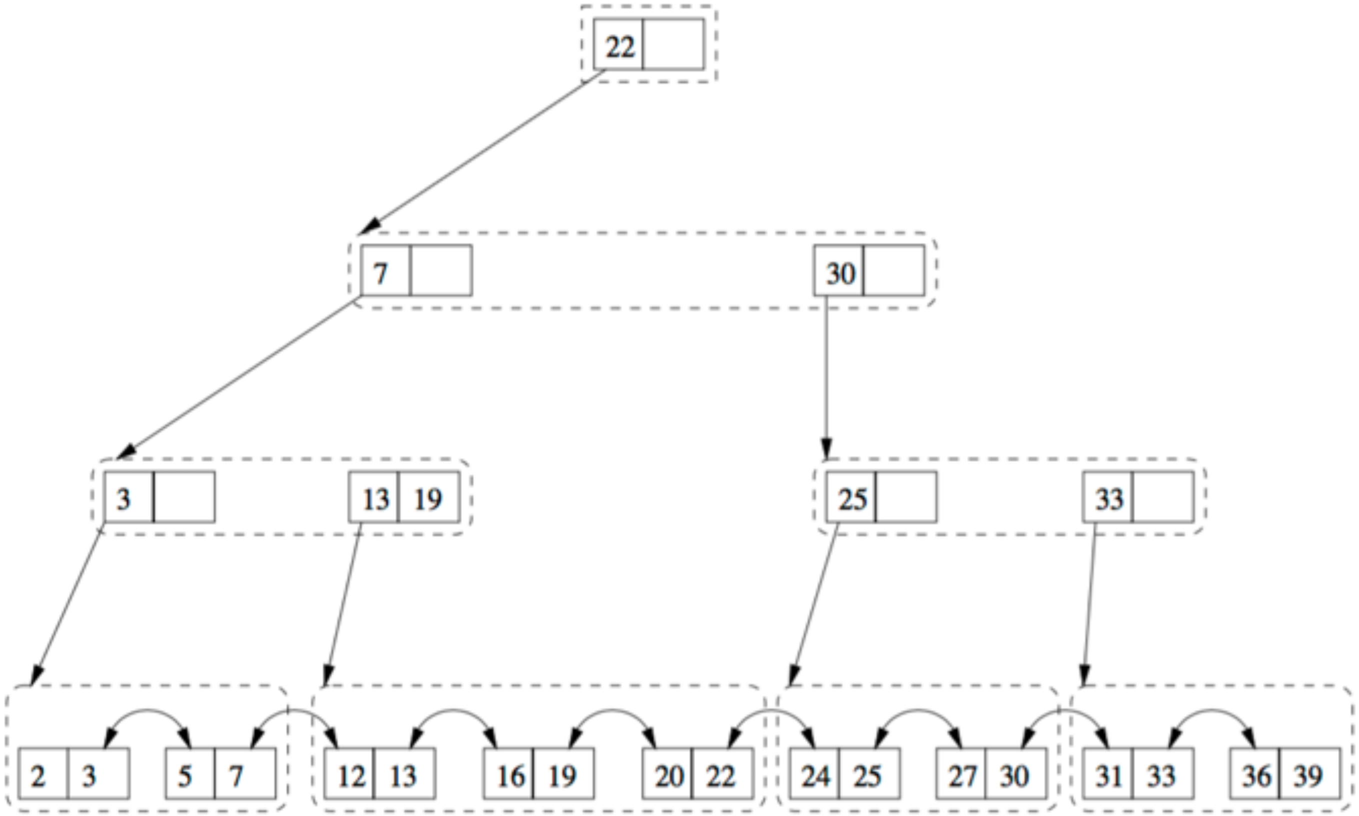
Designed for **disks**!

Node size is equal to **page size**, the goal is to *minimize #random accesses* of pages (wide fanout)

How to make it **memory-friendly**?



Cache-sensitive B+ Trees



Every level is physically stored **contiguously**

Good cache utilization!

Poor updates – needs logic to balance

why?

Tree **height** depends on **#items** inserted

similar to …?

Can we do better for an in-memory search tree?

Maintain order

tree

Maintain few random access

low height

Maintain good cache utilization

access cachelines

Maintain low space complexity

Cheap updates

less logic, avoid rebalancing or splitting

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Enter Tries

Also known as Radix Trees, Prefix Trees, Digital Trees

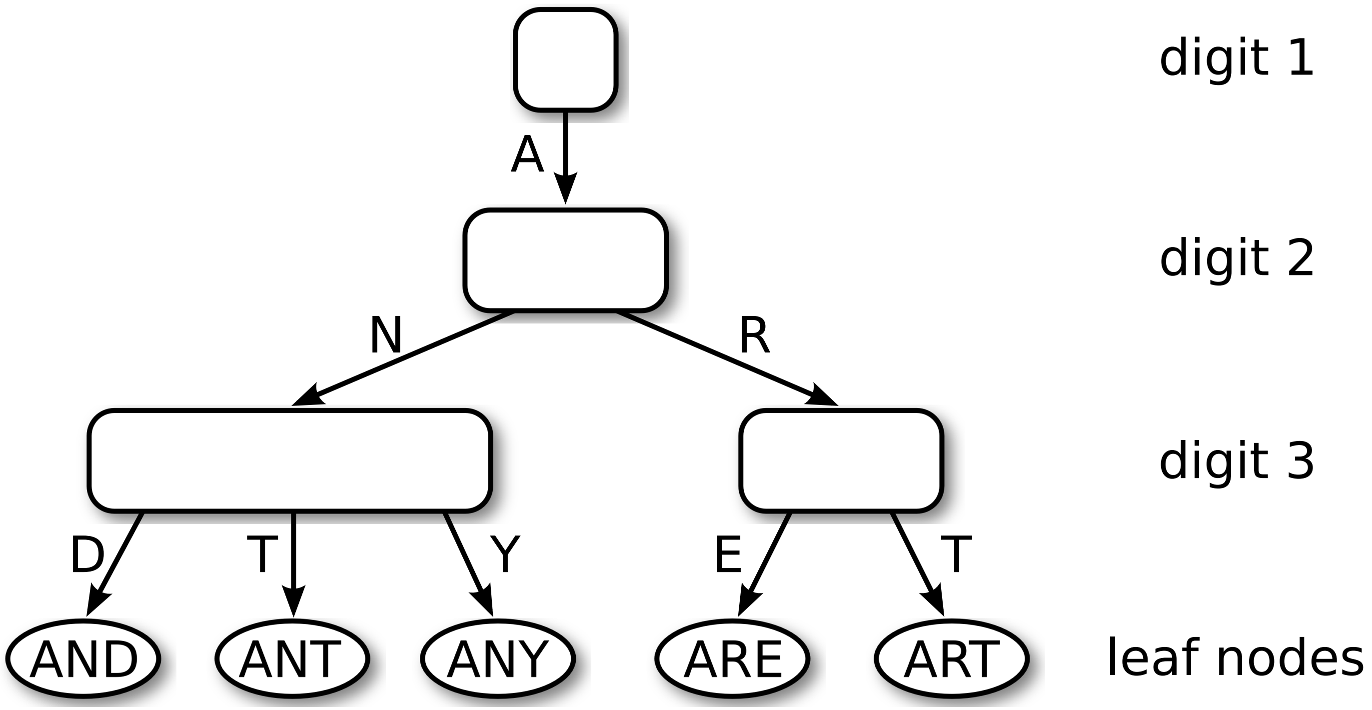
Trie, Radix Tree, Prefix Tree, Digital Tree

Tree **height** depends on **key length *k***

Not on tree (**data**) size

No rebalancing needed!

Automatically get lexicographical order



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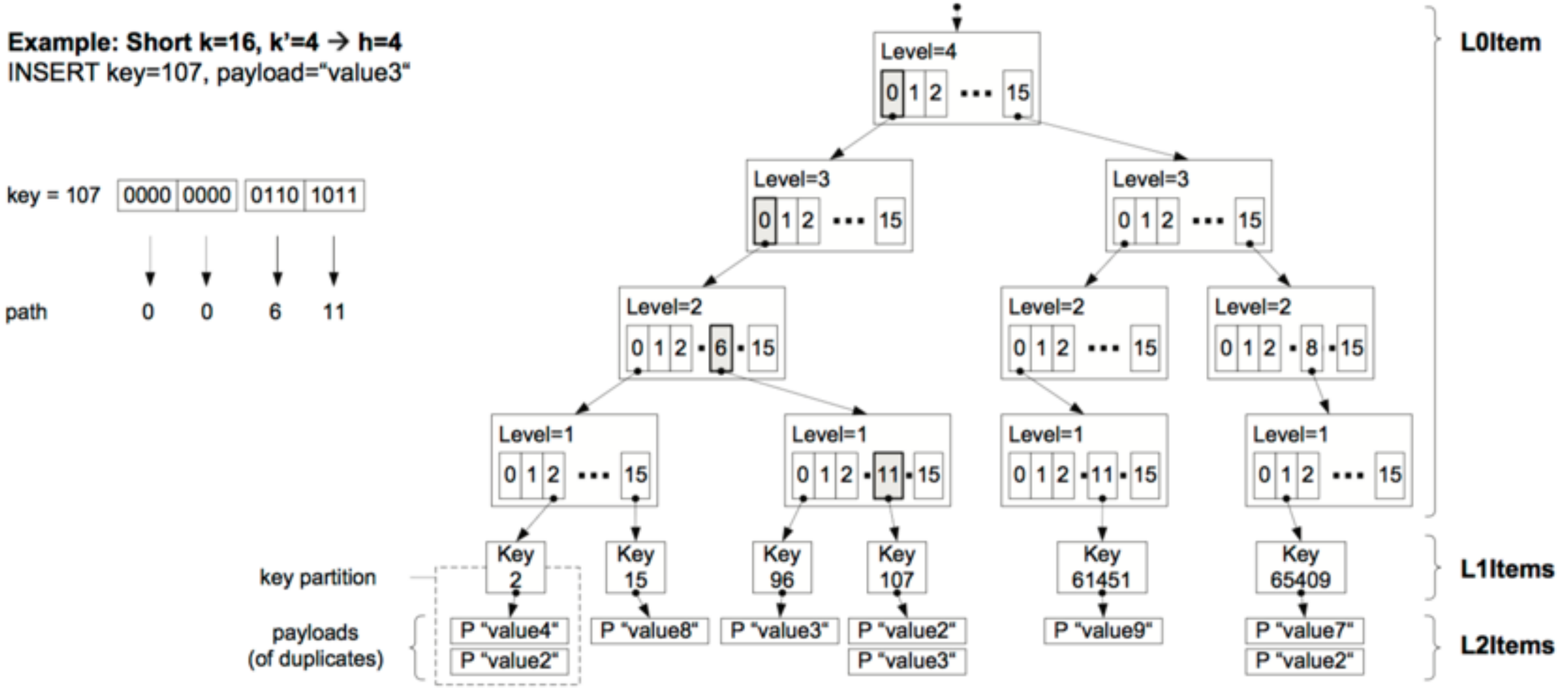
Tries on integers (in binary format)

Every node stores a part of the binary representation ("radix") of the key



Implicit Keys

Significant **space** savings

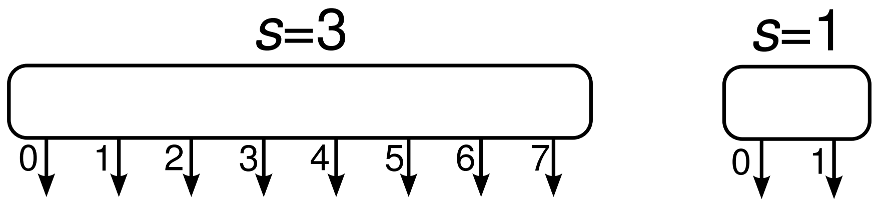
Should all nodes use the **same number** of radix bits?

Adaptive Radix Tree Span

For **binary representations** of keys, the fanout can be configured!

Each node uses *s* bits ("span") of the radix of the key

Hence, an **inner node** is an <u>array of 2^s pointers</u> (with equal number of children)



Tree Size vs. Span

k bit keys & span=s → k/s inner levels & 2^s pointers in each node

let's assume 32 bit keys

span=1 → 32 inner levels & 2 pointers in each node — tall and thin tree

span=2 → 16 inner levels & 4 pointers in each node

span=4 → 8 inner levels & 16 pointers in each node

span=8 → 4 inner levels & 256 pointers in each node — short and fat tree

Height vs. Size Tradeoff

Large s:

small height (fast)

BUT

high space consumption

Small s:

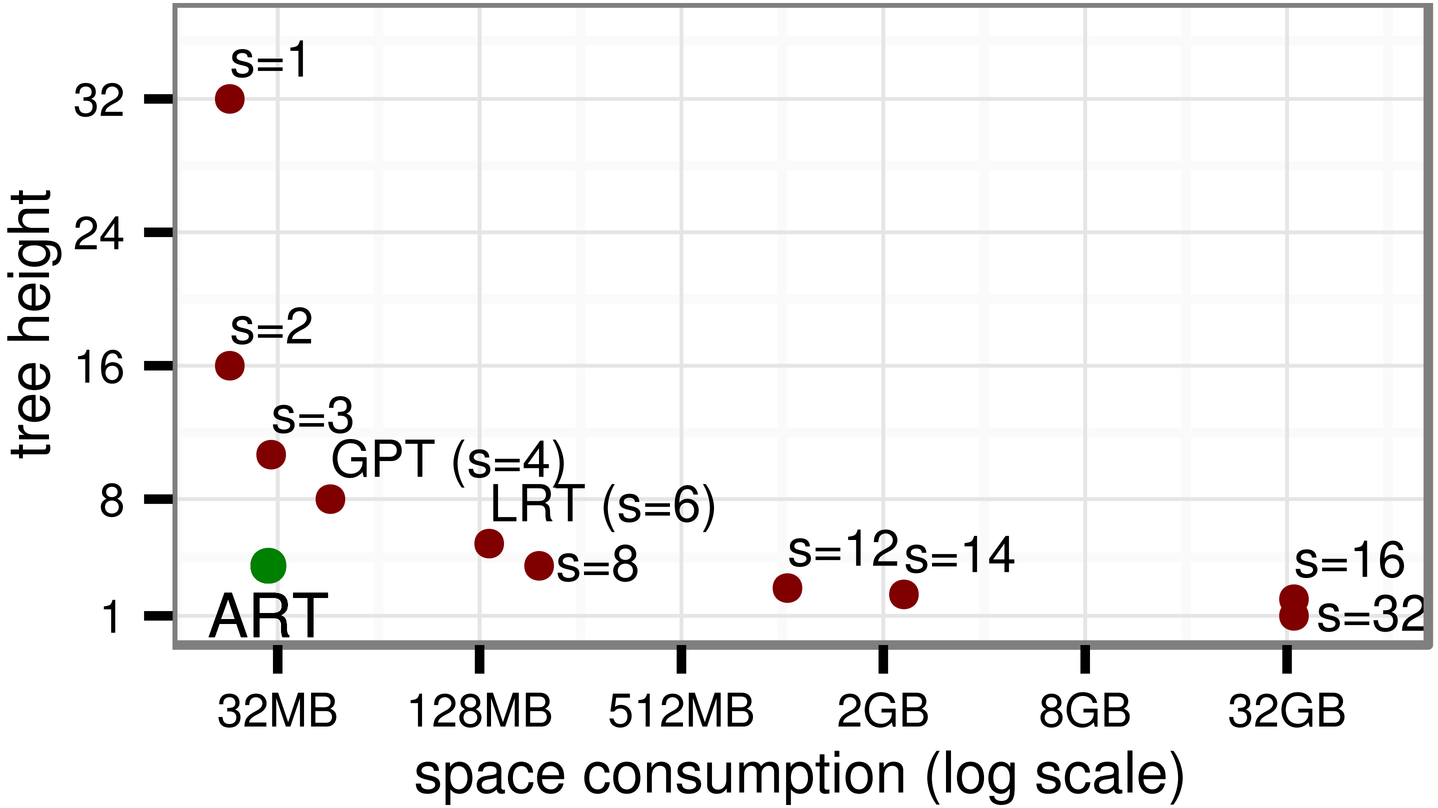
large height (slow)

BUT

low space consumption

ART manages to avoid this tradeoff

How?



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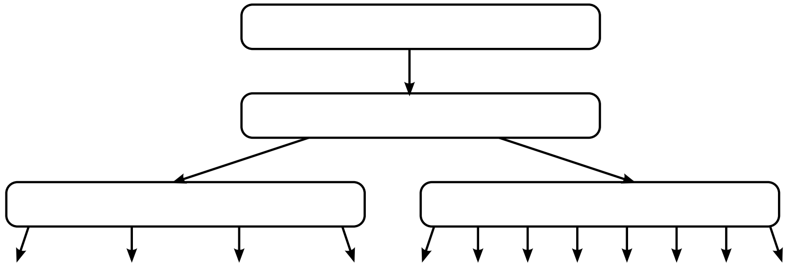
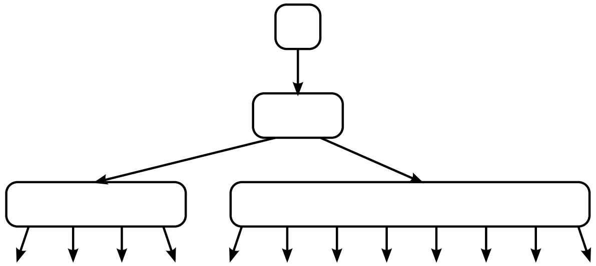
Adaptively Sized Nodes

s = 8: each inner node corresponds **1 byte of the key**

however: **different node sizes** depending on the **actual** number of children



a classical radix tree with fixed-side array nodes

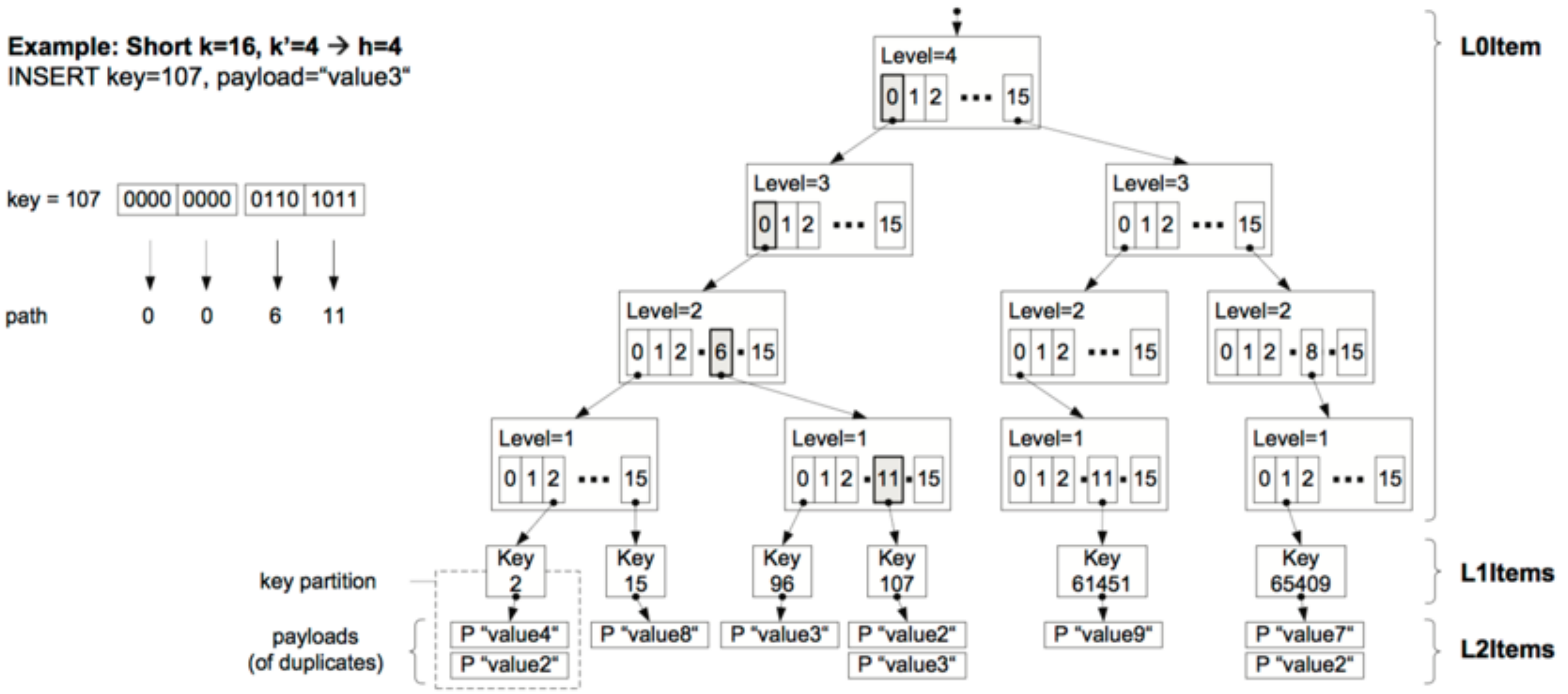


a radix tree with adaptively-sized nodes

design innovation: variable fanout

Remember: what is the goal?

to break a 32-bit key in 4 bytes across 4 levels and reduce the size of the nodes!



More on adaptive nodes

4 node sizes, dynamic decision

explicit keys
both Node4 and Node16
use arrays of size 16

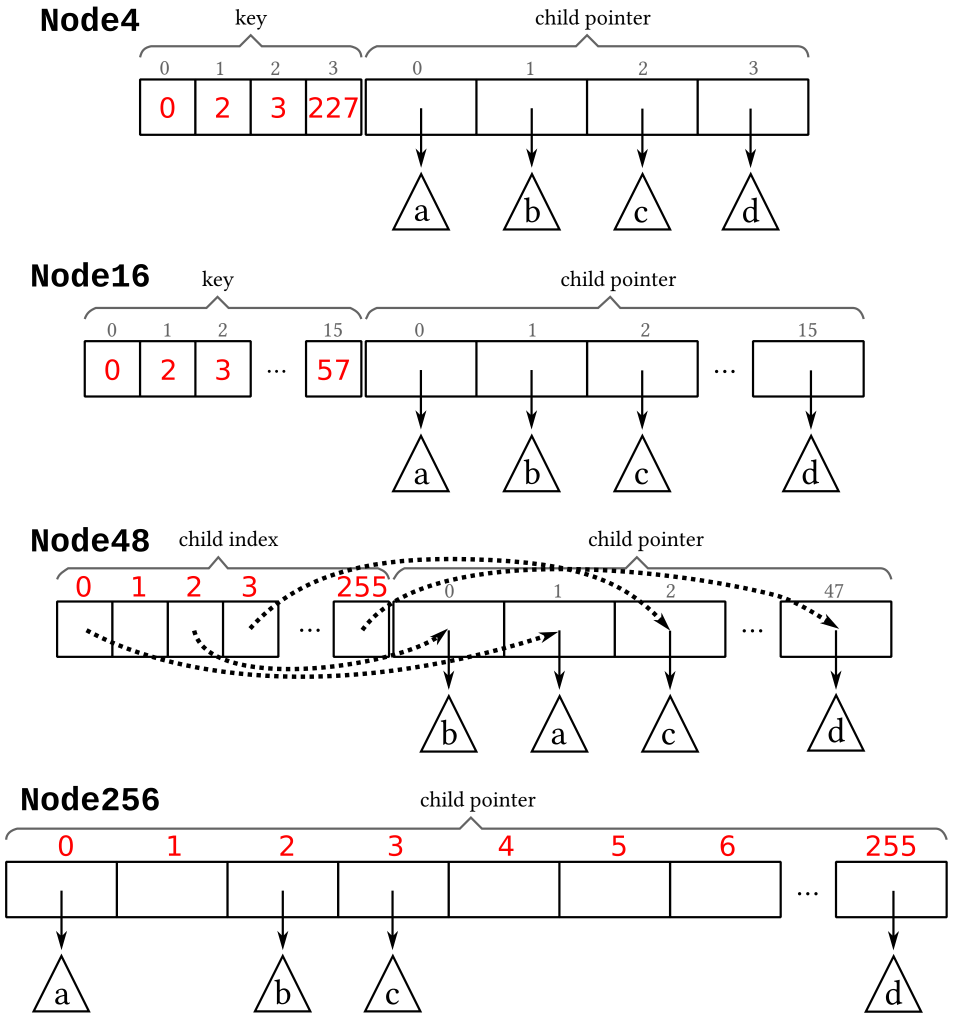
```
typedef struct {
    art_node n;
    unsigned char keys[16];
    art_node *children[16];
} art_node16;
```

indirection index
with implicit keys

```
typedef struct {
    art_node n;
    unsigned char keys[256];
    art_node *children[48];
} art_node48;
```

implicit keys

```
typedef struct {
    art_node n;
    art_node *children[256];
} art_node256;
```



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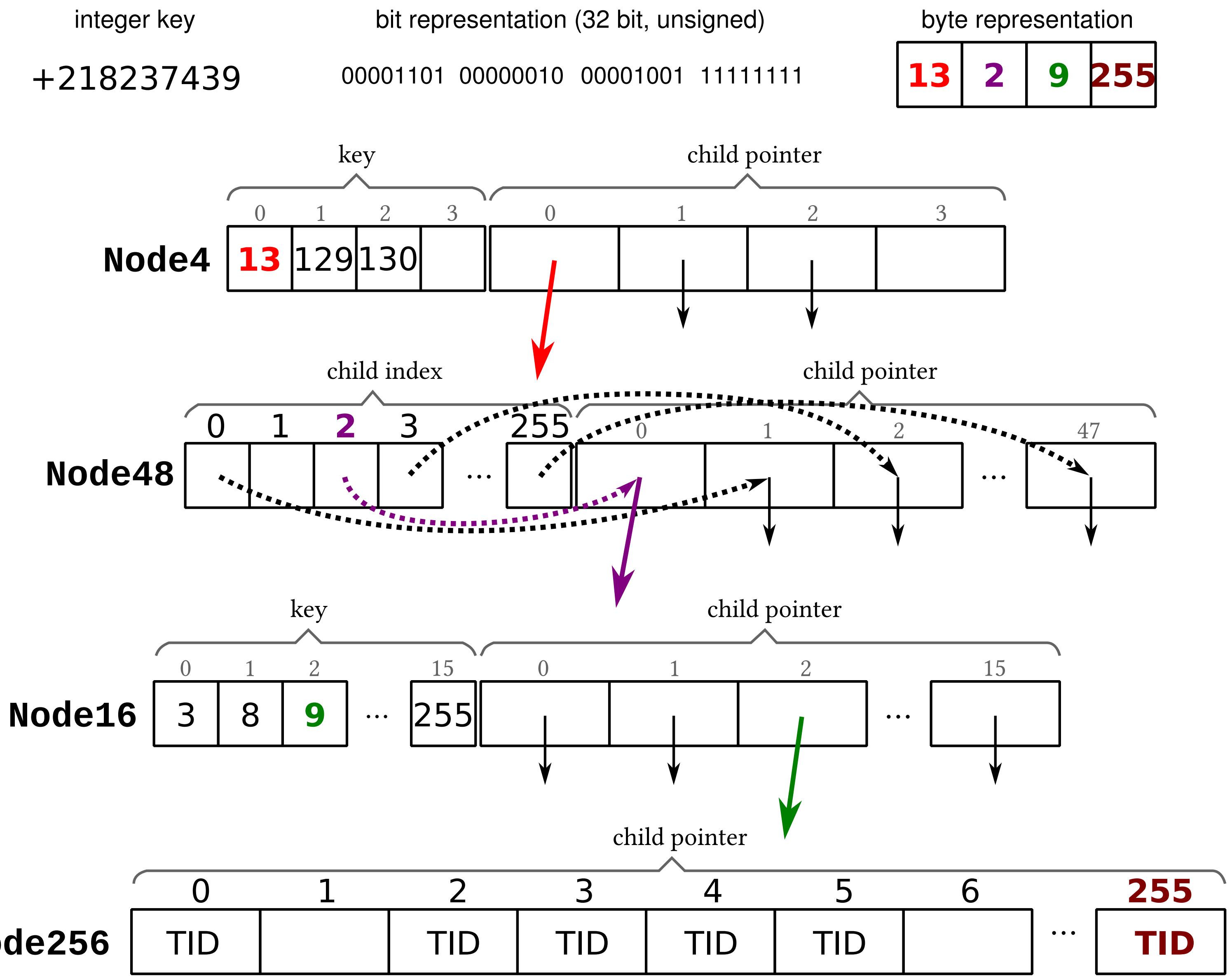
ART Traversal



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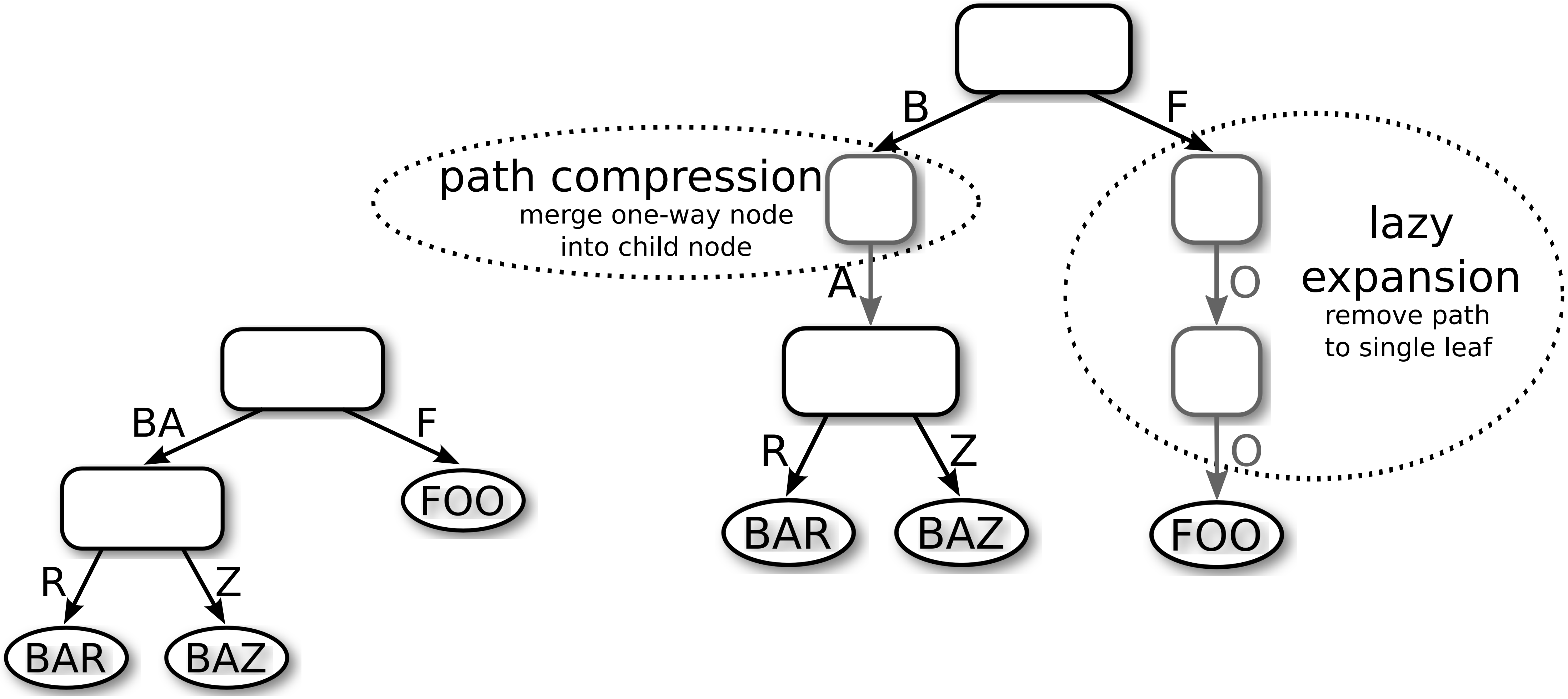
Optimizations: Remove one-way nodes



Supporting various data types

Native support for:

String

Integers (binary representation)

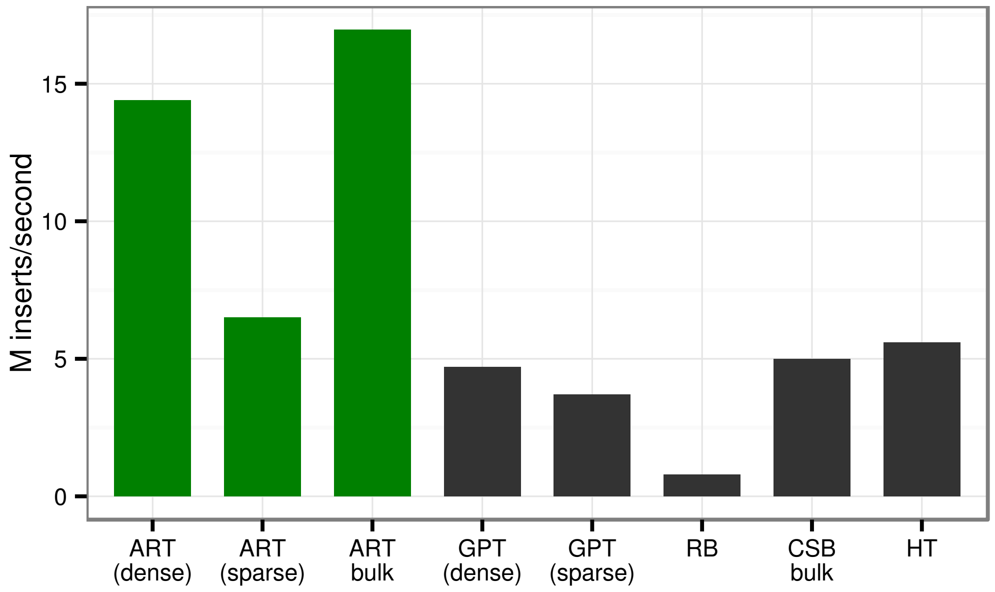
Require transformations for:

floats, Unicode, signed, null, composite

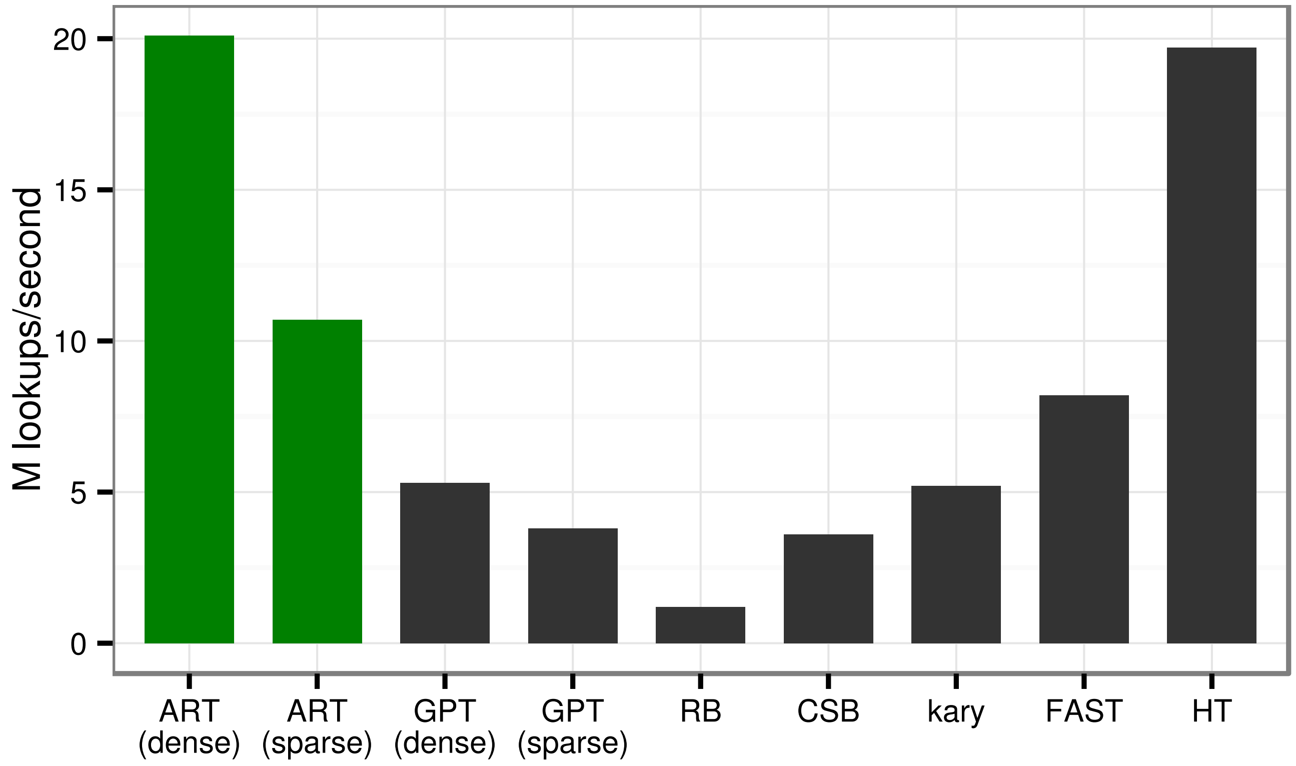
when?

Evaluation

Insert performance (4B keys)



Lookup performance (4B keys)



GPT: Generalized Prefix Tree, Boehm et al., BTW 2011

RB: Red-Black Tree

CSB: Cache-Sensitive B+Tree, Rao and Ross, SIGMOD 2000

kary: K-ary Search Tree, Schlegel et at., Damon 2009

FAST: Fast Architecture Sensitive Tree, Kim et al., SIGMOD 2010

HT: Chained Hash Table

Cache Efficiency

PERFORMANCE COUNTERS PER LOOKUP.

	65K			16M		
	ART (d./s.)	FAST	HT	ART (d./s.)	FAST	HT
Cycles	40/105	94	44	188/352	461	191
Instructions	85/127	75	26	88/99	110	26
Misp. Branches	0.0/0.85	0.0	0.26	0.0/0.84	0.0	0.25
L3 Hits	0.65/1.9	4.7	2.2	2.6/3.0	2.5	2.1
L3 Misses	0.0/0.0	0.0	0.0	1.2/2.6	2.4	2.4

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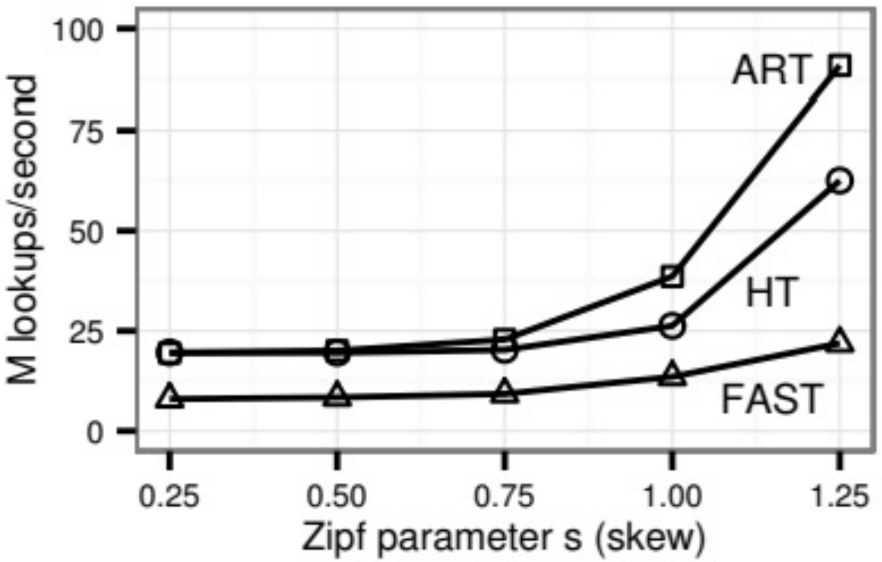
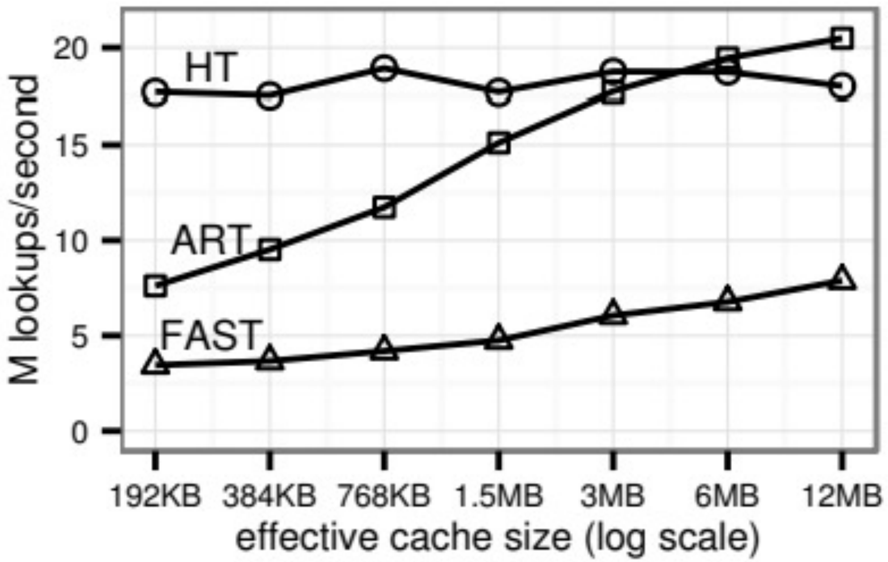
Skewed Search & Impact of Cache Size





ART: adjacent items are in the same node/subtree

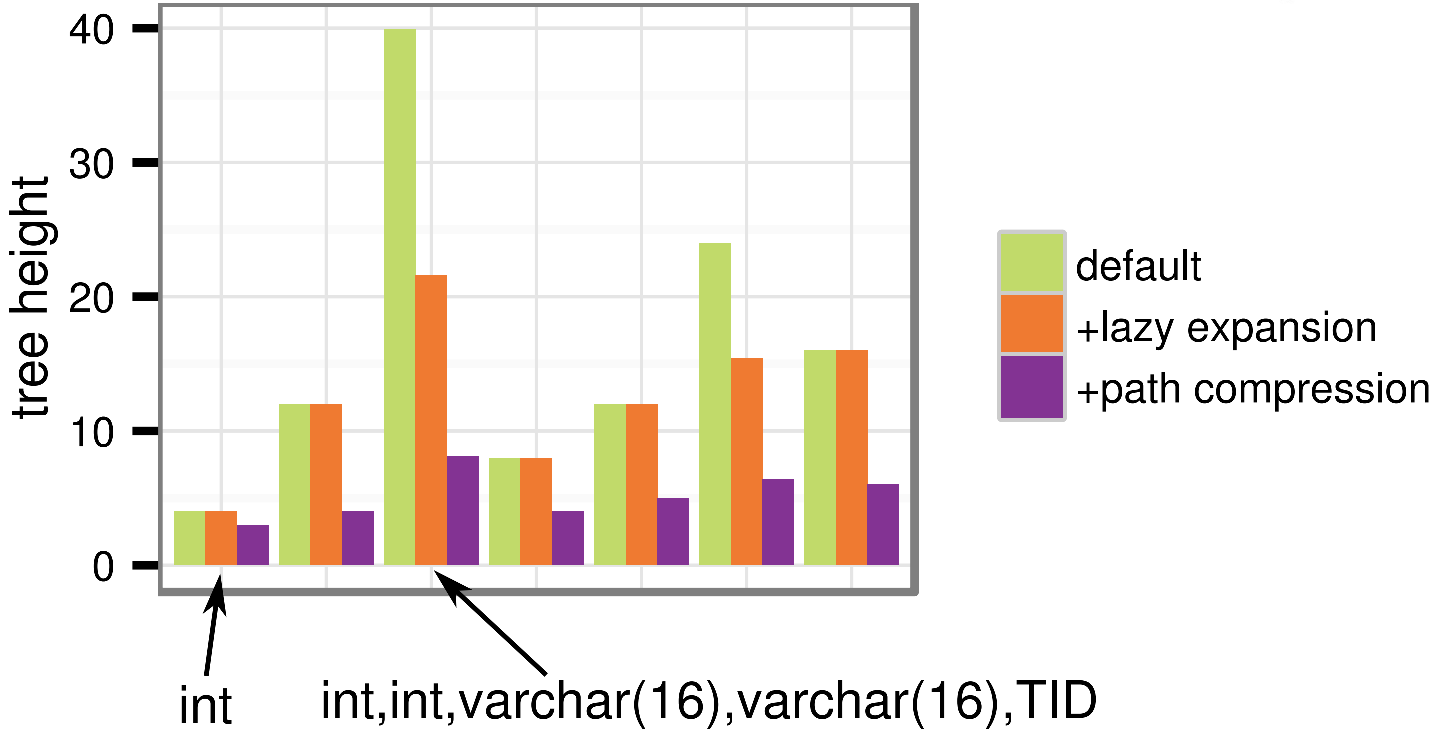
HT: adjacent items are in different buckets

ART: no evictions, fewer misses overall

HT: data is randomly distributed more misses

Tree Height in TPCC

#	Relation	Cardinality	Attribute Types	Space
1	item	100,000	int	8.1
2	customer	150,000	int,int,int	8.3
3	customer	150,000	int,int,varchar(16),varchar(16),TID	32.6
4	stock	500,000	int,int	8.1
5	order	22,177,650	int,int,int	8.1
6	order	22,177,650	int,int,int,int,TID	24.9
7	orderline	221,712,415	int,int,int,int	16.8



Without the height optimization the height can be the length of the keys → can be prohibitively high

why? what is the height of a B+ Tree?

Space Efficiency for TPCC

MAJOR TPC-C INDEXES AND SPACE CONSUMPTION PER KEY USING ART.

#	Relation	Cardinality	Attribute Types	Space
1	item	100,000	int	8.1
2	customer	150,000	int,int,int	8.3
3	customer	150,000	int,int,varchar(16),varchar(16),TID	32.6
4	stock	500,000	int,int	8.1
5	order	22,177,650	int,int,int	8.1
6	order	22,177,650	int,int,int,int,TID	24.9
7	orderline	221,712,415	int,int,int,int	16.8

Conclusions

Radix Trees can be used as a **generalized** index

for multiple data types

space efficient

with excellent performance

thus, combining:

range query support of <u>search trees</u>

point lookup efficiency of <u>hash indexes</u>

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