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CS 561: Data Systems Architectures

class 11

Adaptive Radix Trees

Prof. Manos Athanassoulis

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

Indexing is key to database performance

B+ Trees dominate disk-based indexes

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

BUT

Hash tables are unordered (no range queries)

Search trees are slow

can we do better?

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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?

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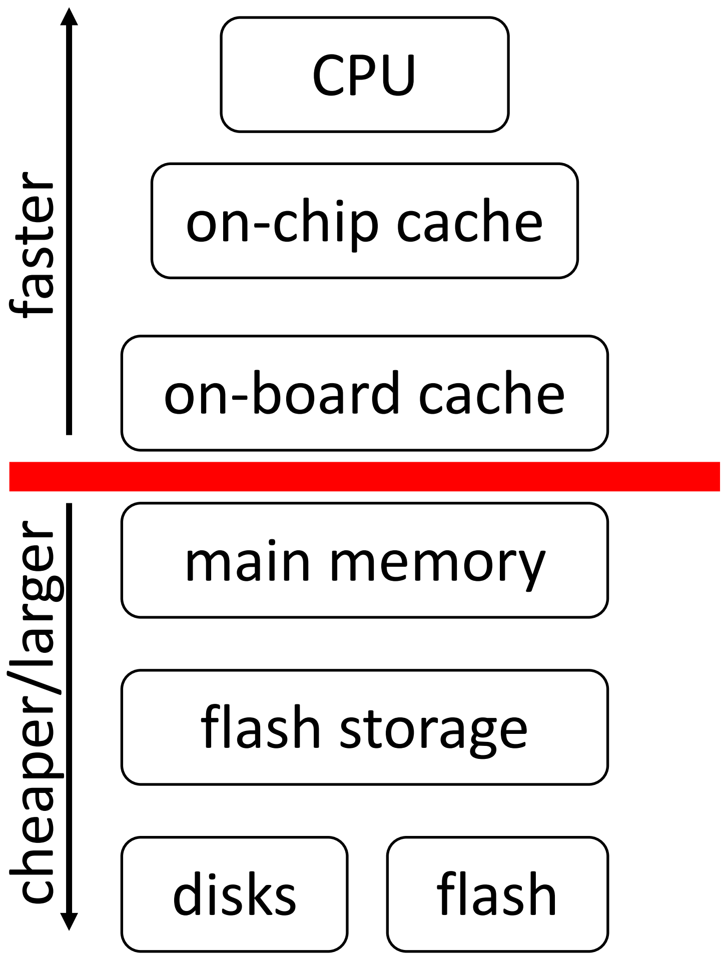
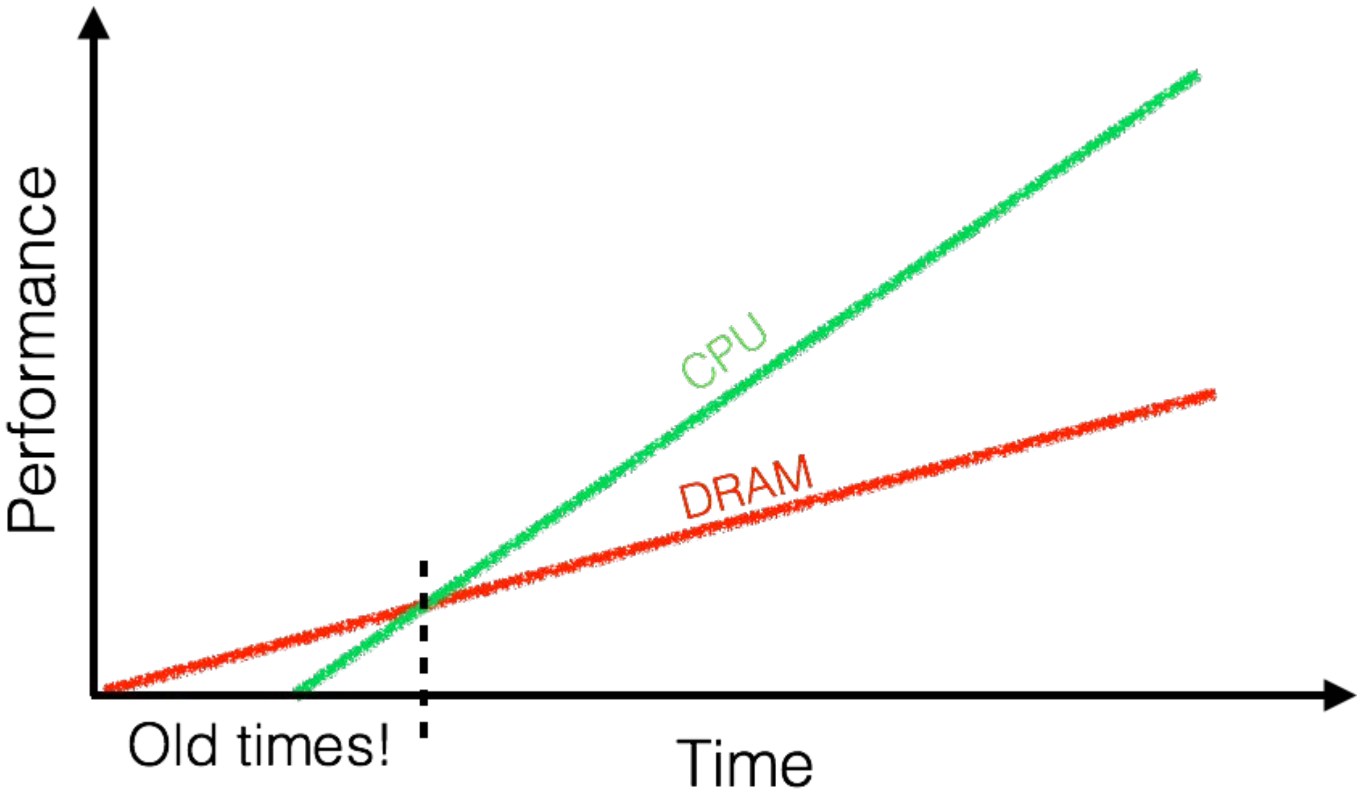
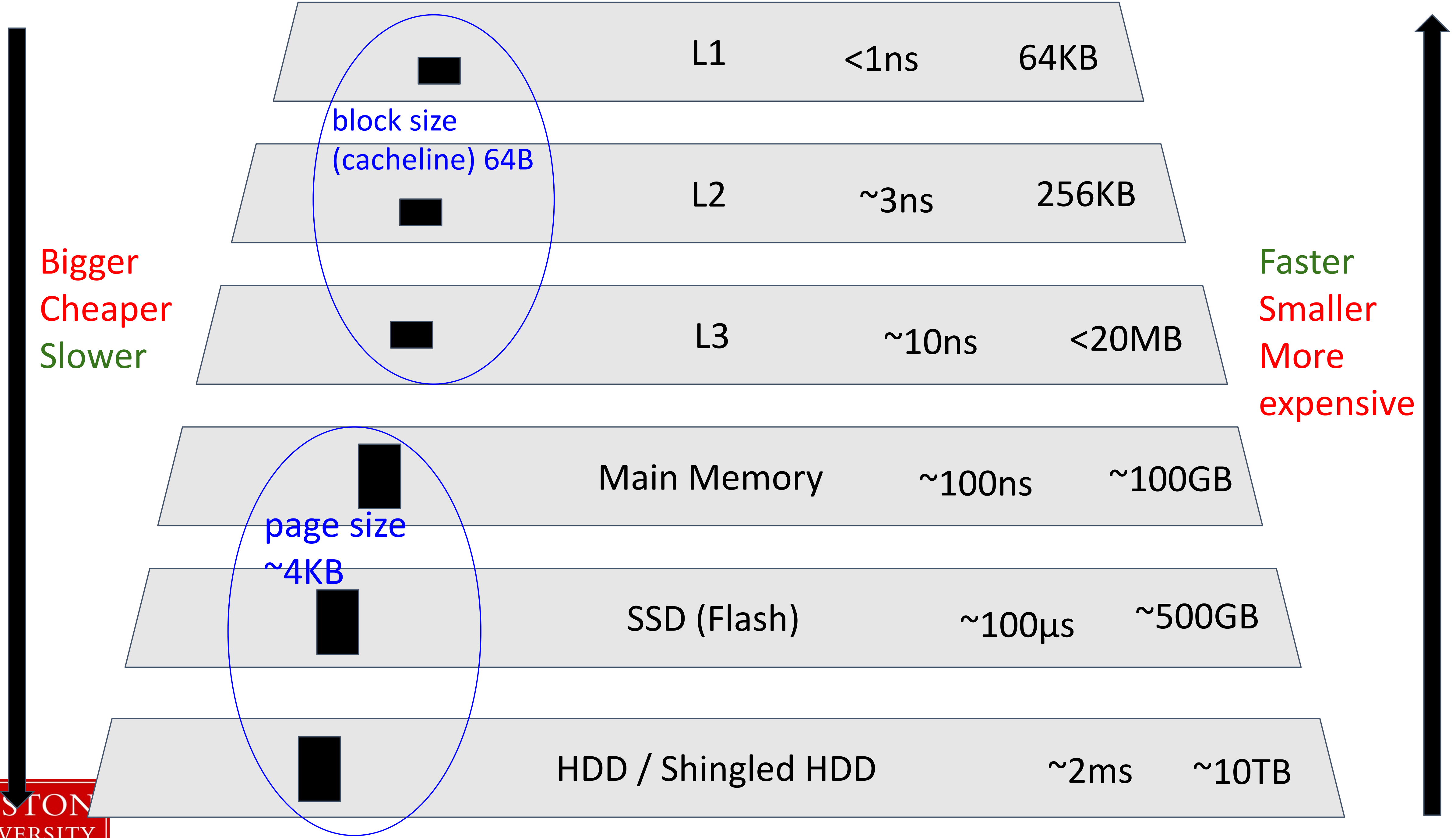
Reminder: Memory Wall





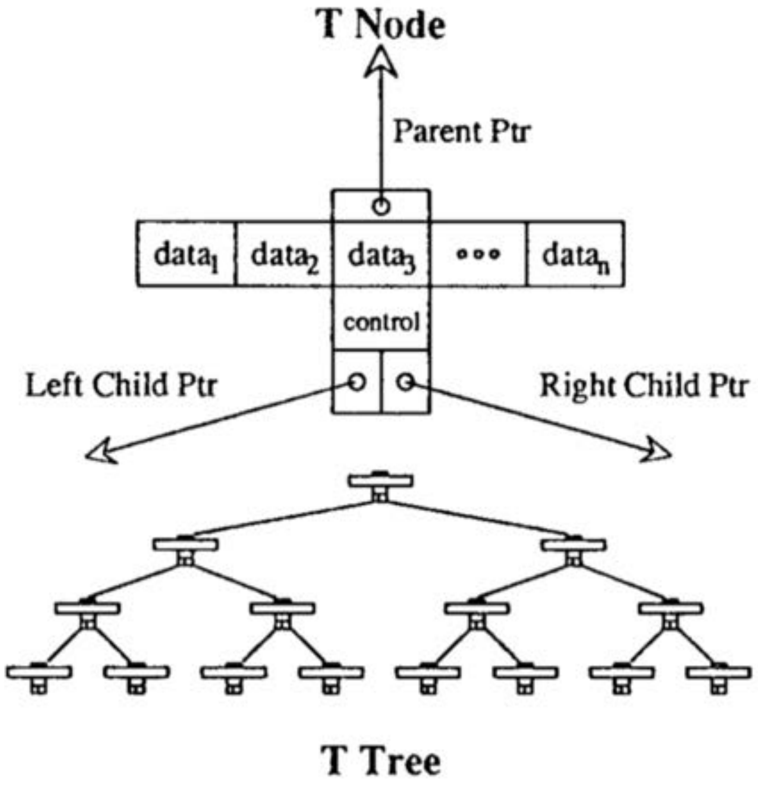

L1
<1ns
64KB
block size
(cacheline) 64B
L2
~3ns
256KB
Bigger
Cheaper
Slower
L3
~10ns
<20MB
Faster
Smaller
More
expensive
Main Memory
~100ns
~100GB
page size
~4KB
SSD (Flash)
~100µs
~500GB
HDD / Shingled HDD
~2ms
~10TB

In-Memory Search Trees: T-Trees

Fat nodes (~cacheline size) with two children

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

Unpredictable pointer chasing

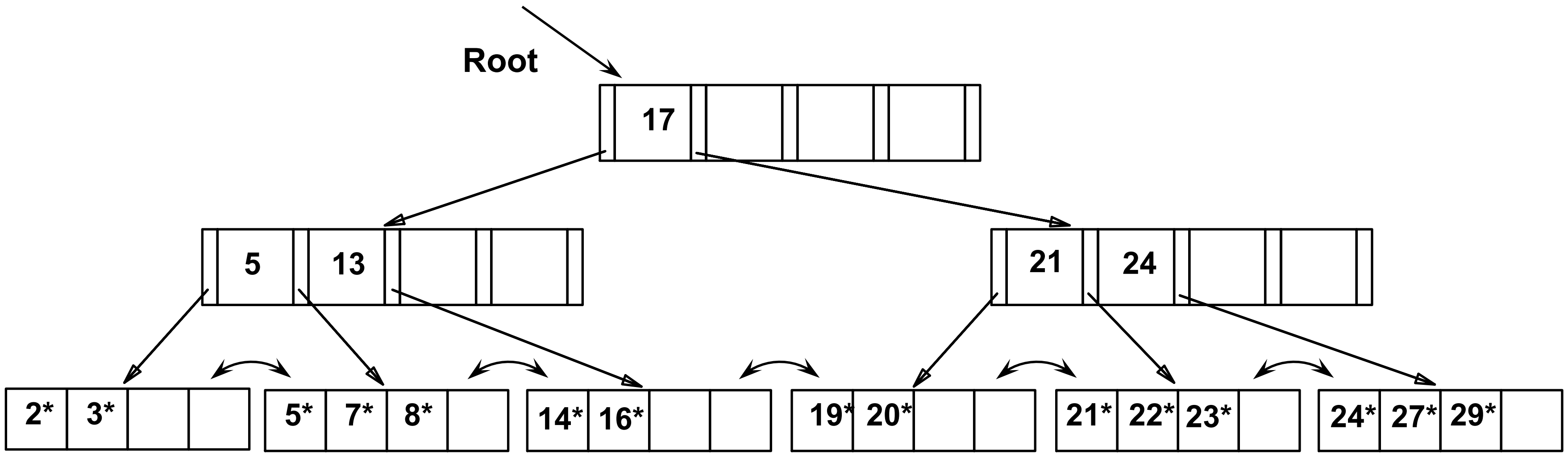


Are B+ Trees good for in-memory execution?

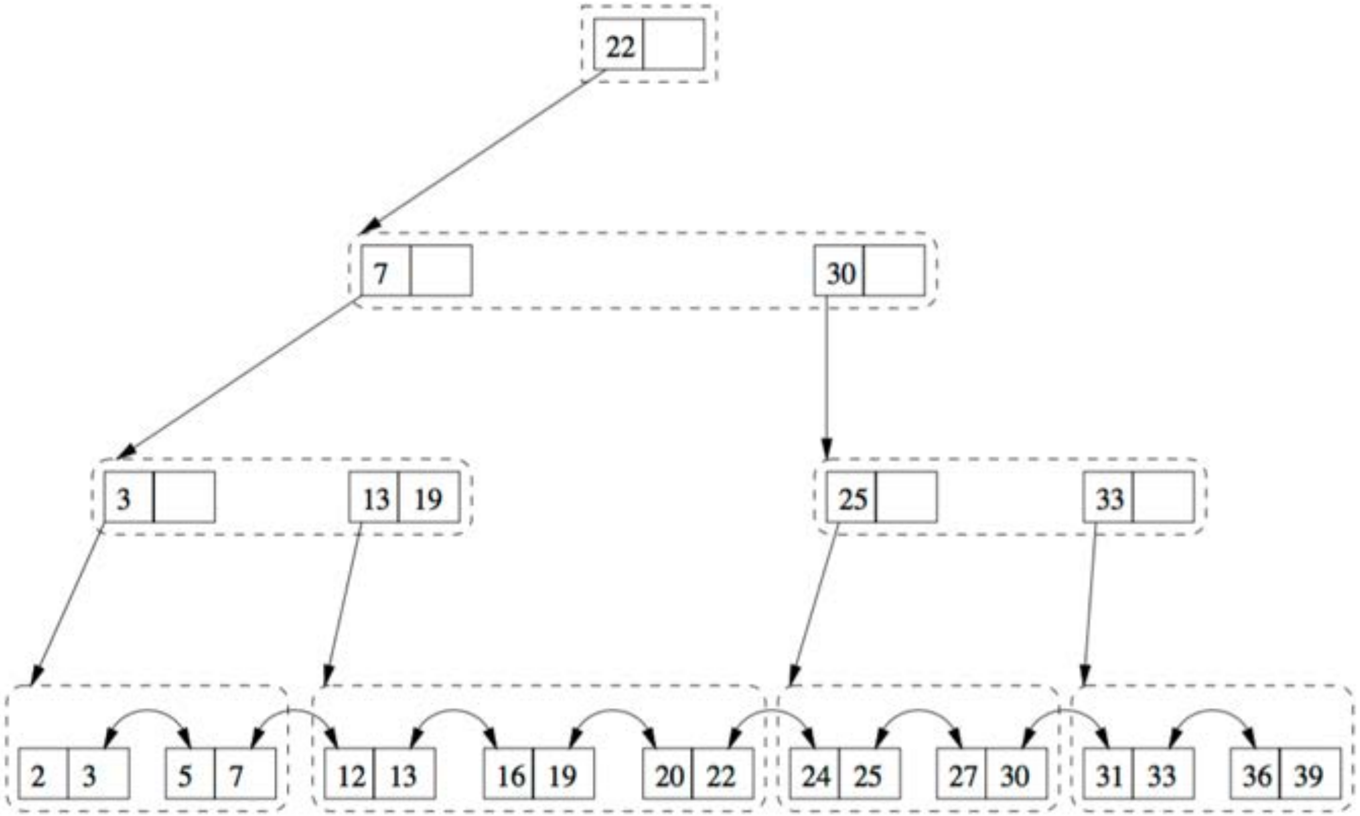
Designed for disks!

Nodes have 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

Tree height depends on #items inserted

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

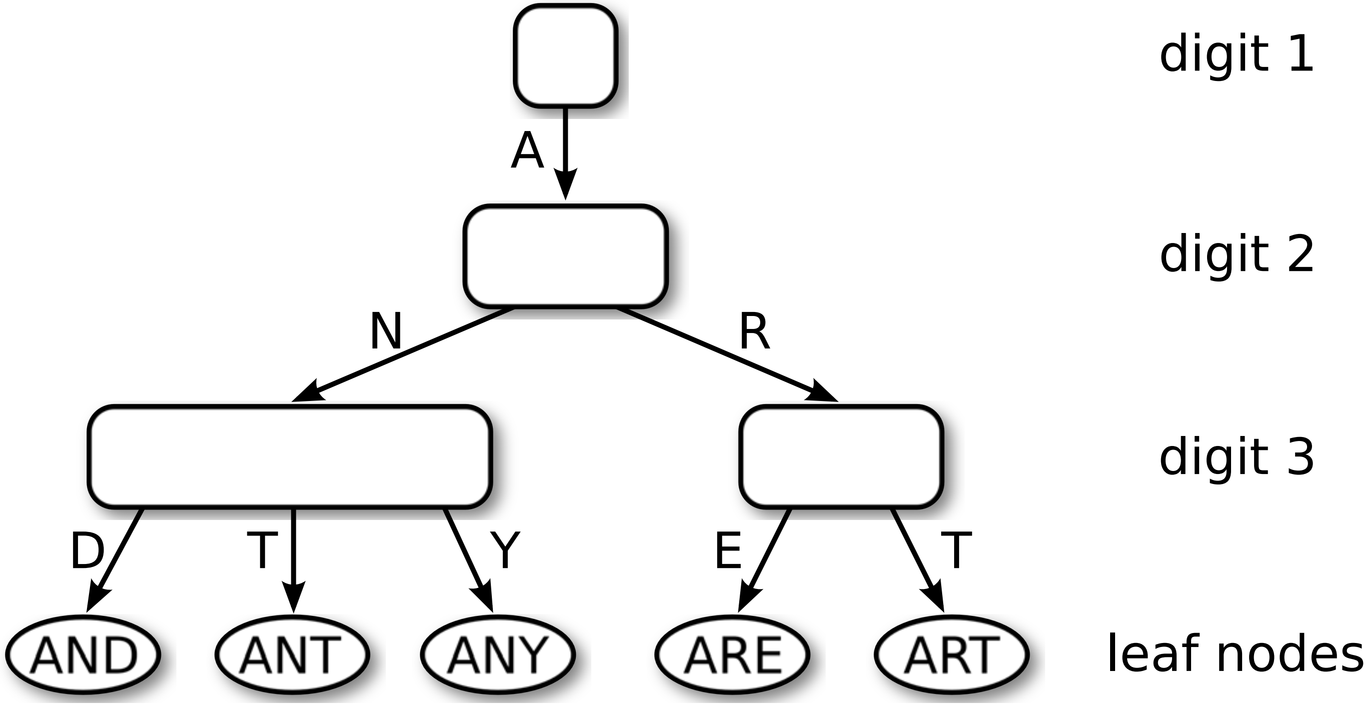
Trie, Radix Tree, Prefix Tree, Digital Tree

Tree height depends on key length k

Not on tree (data) size

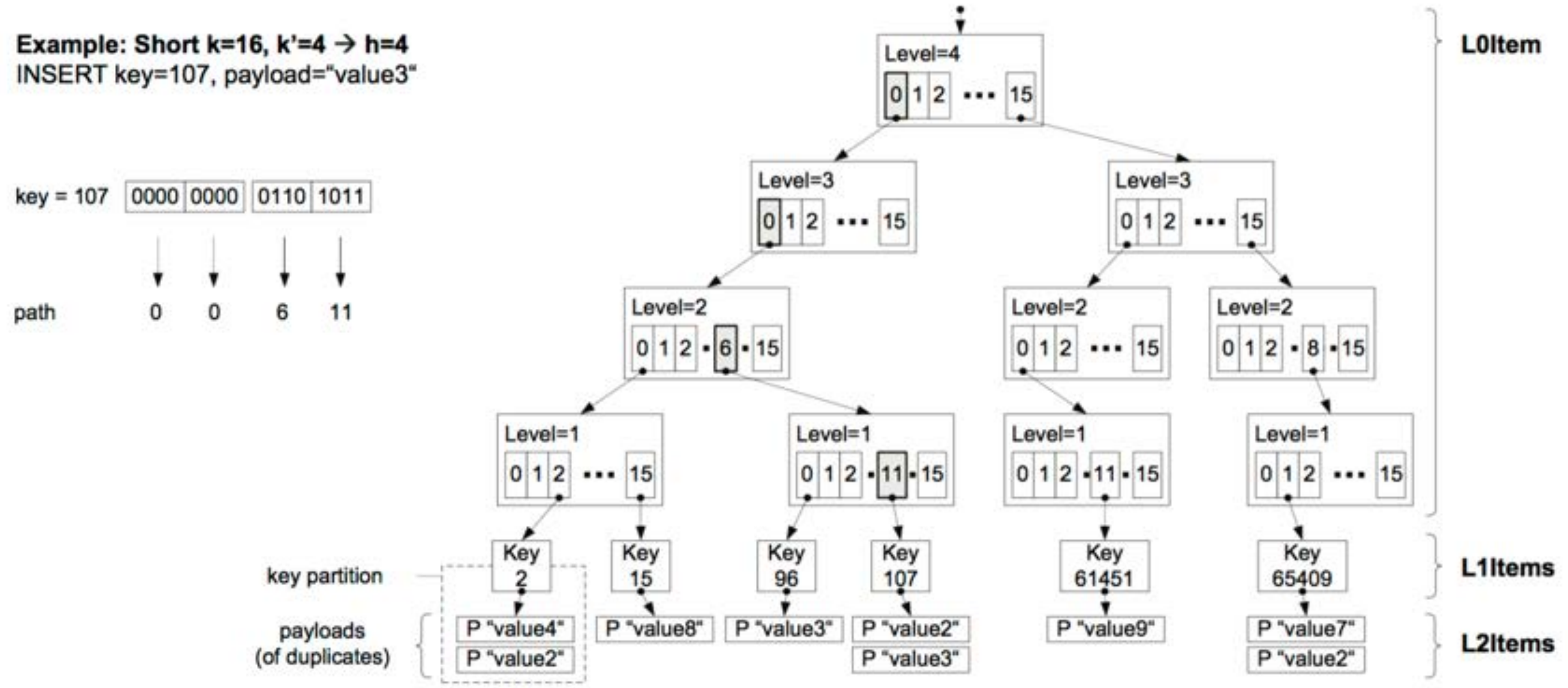
No rebalancing needed!

Automatically get lexicographical order



Tries on integers (in binary format)

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



Implicit Keys

Significant space savings

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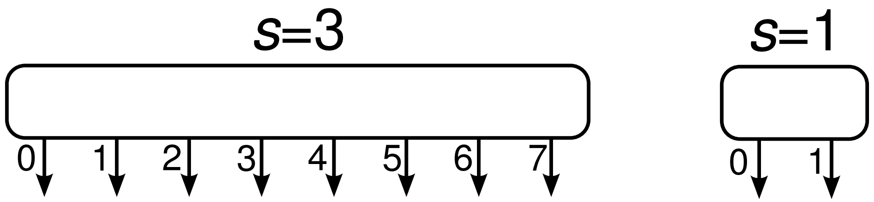
Should all nodes use the same number of radix bits?

Adaptive Radix Tree Span

For binary keys, the fanout can be configured!

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

Hence, an inner is an array of 2^s pointers (with equal number of children)



Tree Size vs. Span

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

32 bit keys & span=1 → 32 inner levels & 2 pointers in each node

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

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

32 bit keys & span=8 → 4 inner levels & 256 pointers in each node

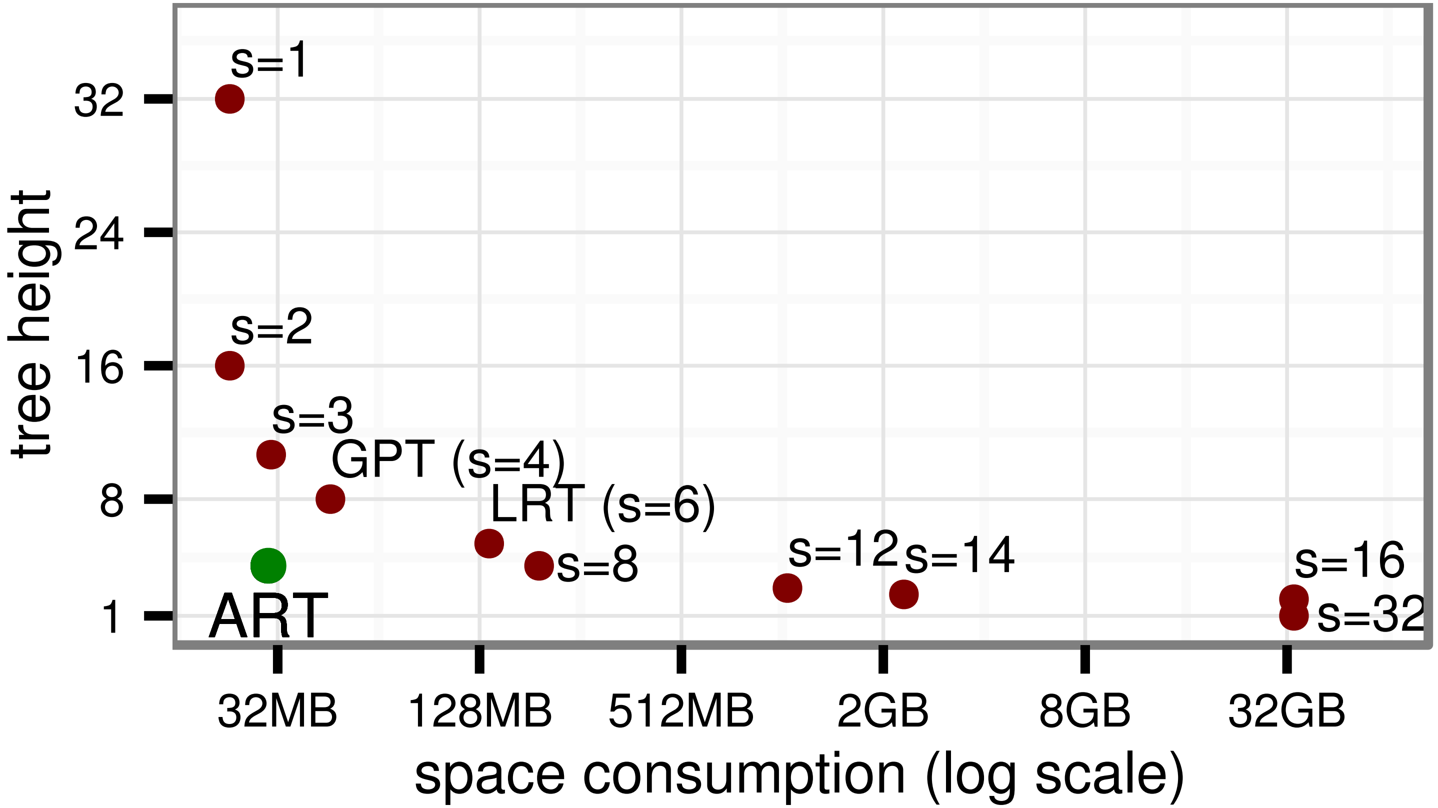
Height vs. Size Tradeoff

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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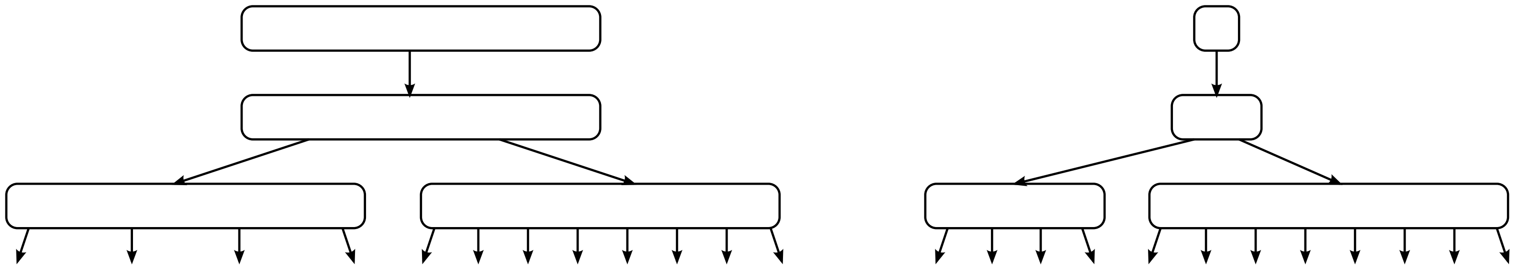
Adaptively Sized Nodes

s=8: each inner node maps 1 byte of the key to the child node

different node sizes, depending on the number of children

variable fanout



More on adaptive nodes

4 node sizes, dynamic decision

explicit keys
both Node4 and Node16
use arrays of size 16

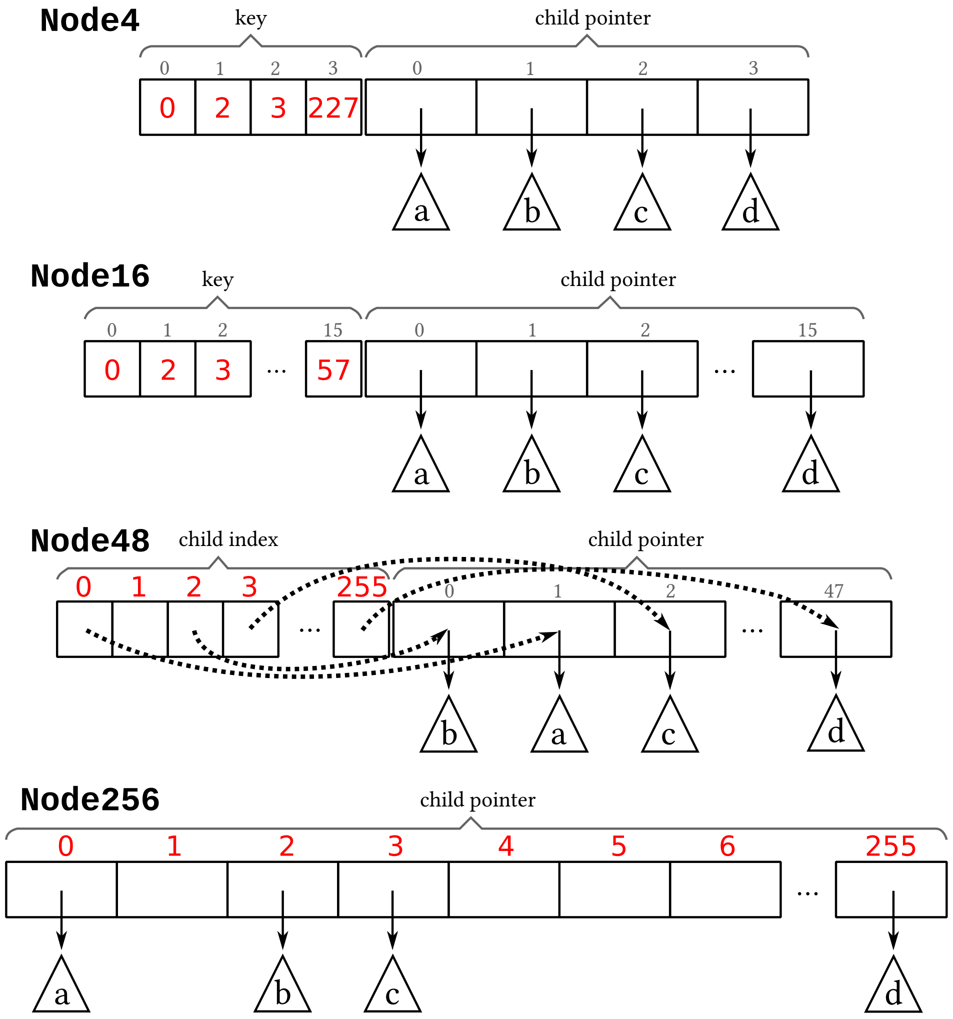
```
typedef struct {
    art_node n;
    unsigned char keys[16];
    art_node *children[16];
} art_node16;
```

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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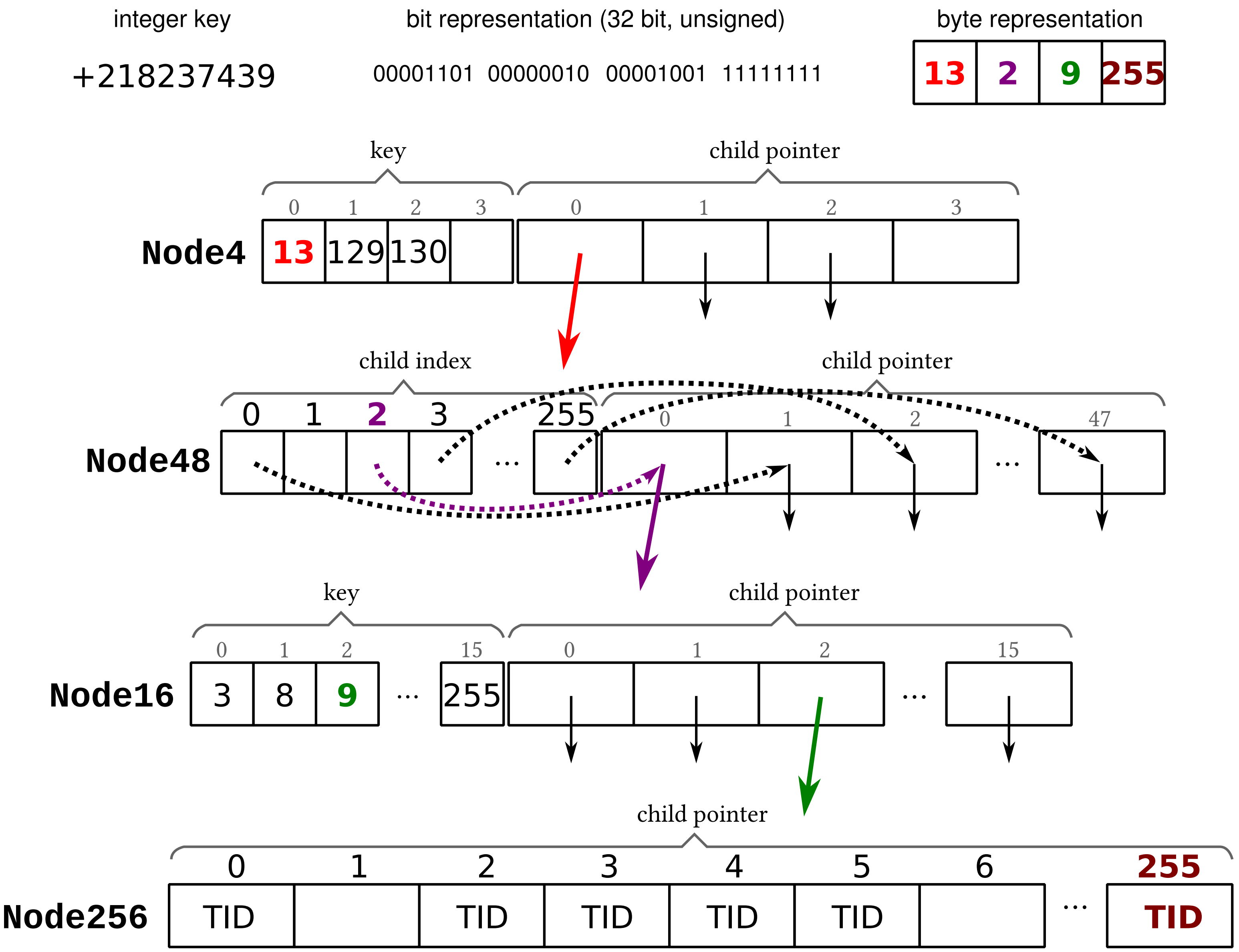
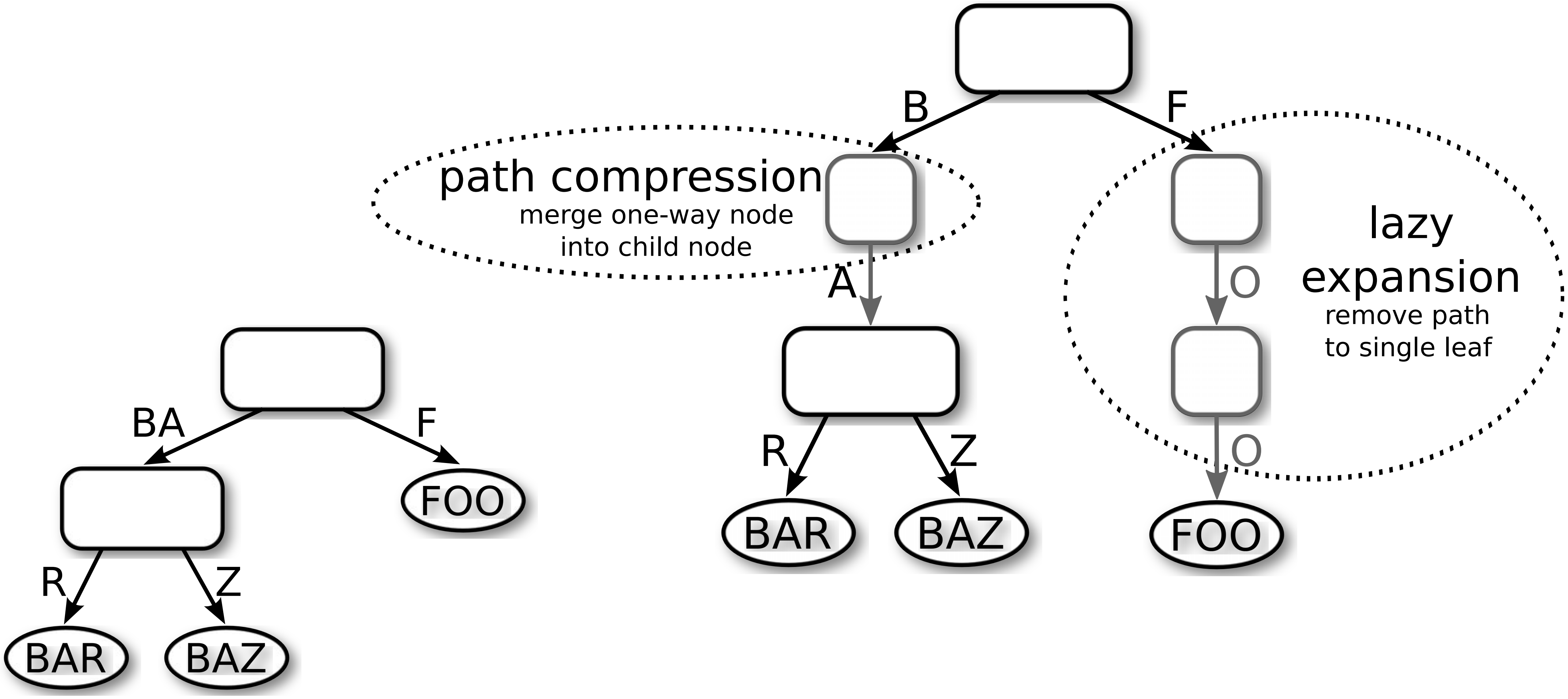
ART Traversal



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?

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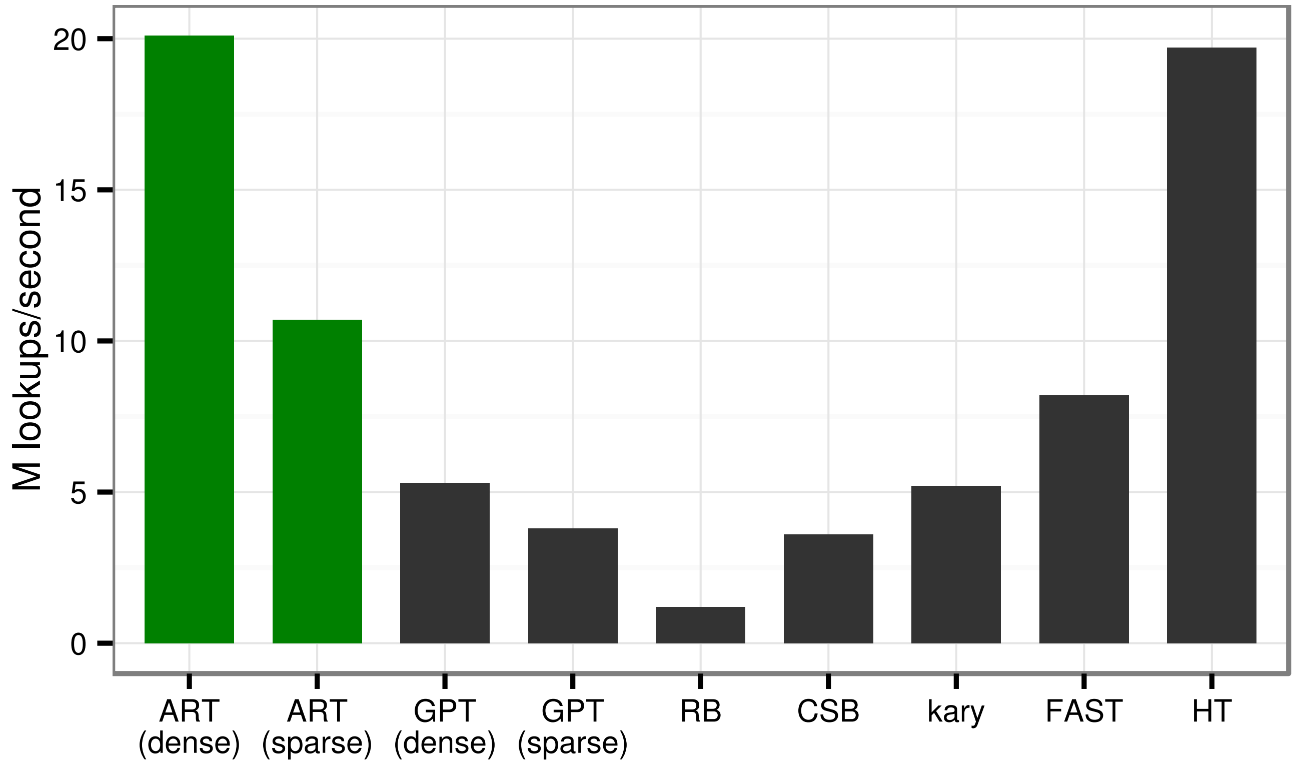
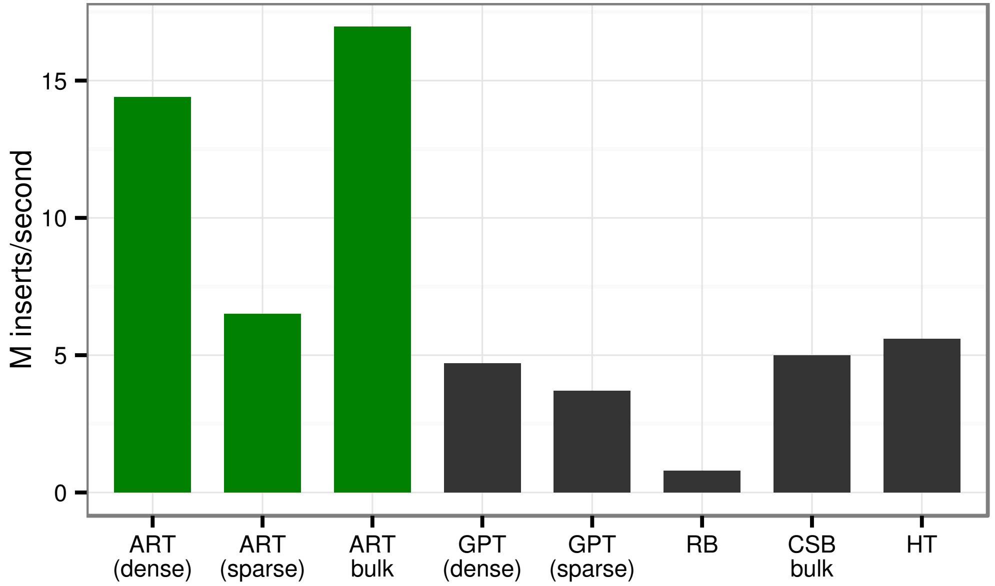
Evaluation

Lookup performance (4B keys)



Insert 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

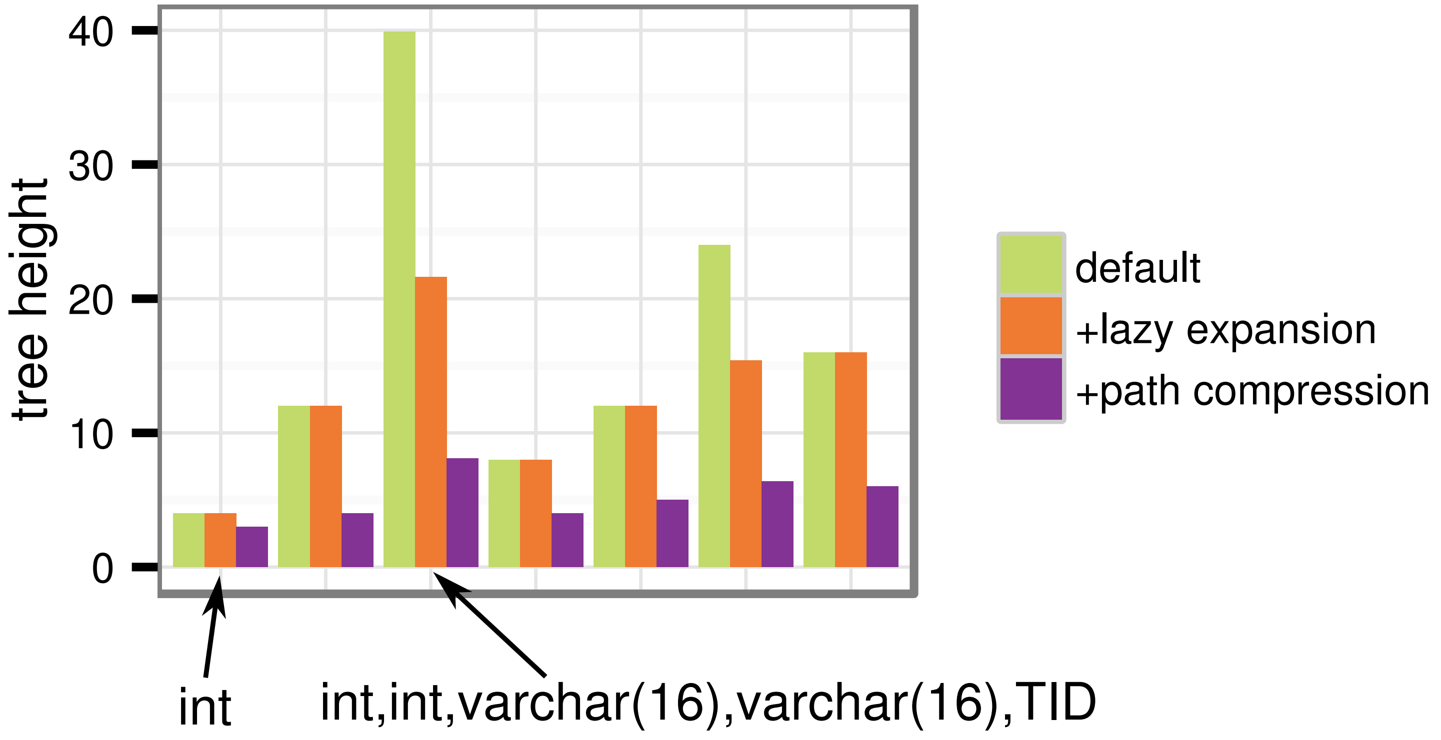
HT: Chained Hash Table

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

Reducing Tree Height in TPCC

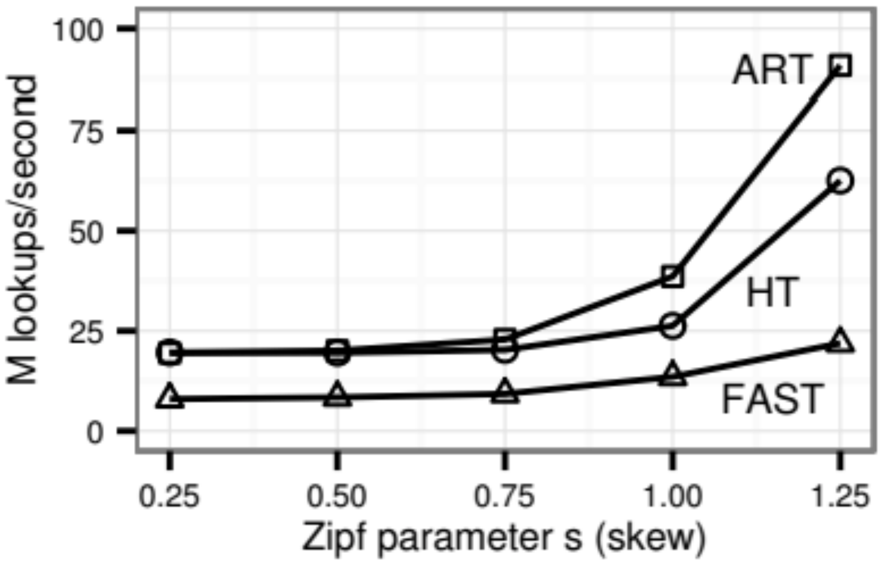


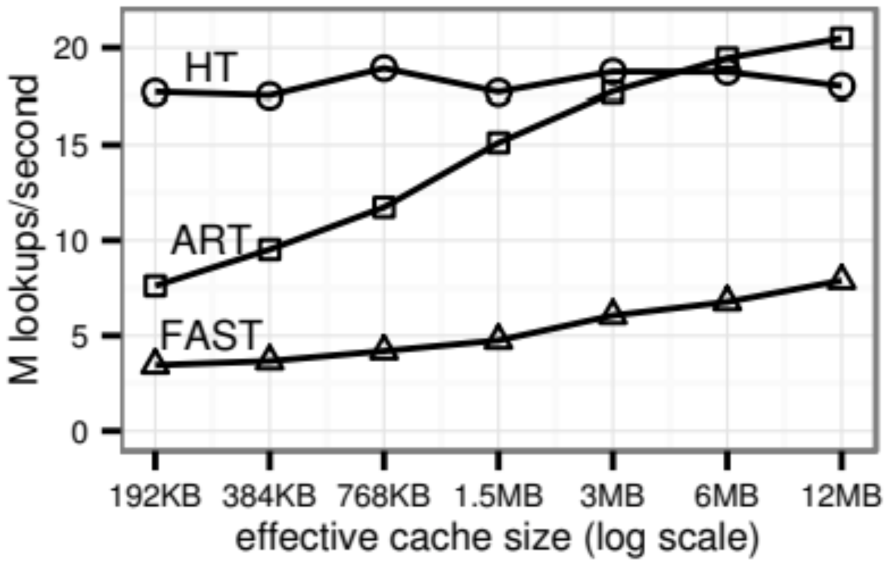
Without the height optimization the height can be the length of the keys → can be prohibitively high

why?

what is the height of a B+ Tree?

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 missed overall
HT: data is randomly distributed more misses

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

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Conclusions

Radix Trees can be used as a generalized index

for multiple data types

space efficient

with excellent performance

thus, combining the benefit of search trees (supports ranges) with lookup efficiency of hash tables

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