HOT Inside

The Technical Architecture

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May 22, 2008

Overview

- PostgreSQL MVCC
- Motivation for Improvement
- HOT Basics
- HOT Internals
- Limitations
- Performance Numbers and Charts

What Does HOT Stand For ?

- Heap Organized Tuples
- Heap Optimized Tuples
- Heap Overflow Tuples
- Heap Only Tuples

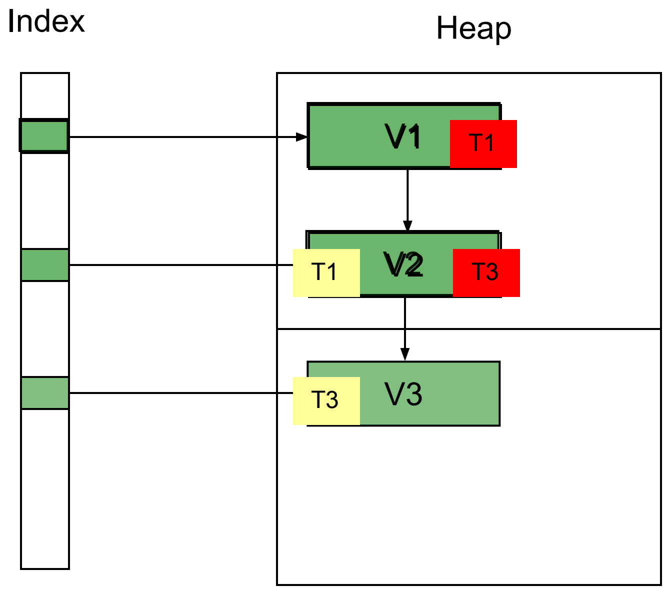
Credits

- Its not entirely my work
- Several people contributed, some directly, many indirectly
  - Simon Riggs – for writing initial design doc and getting me involved
  - Heikki – for code review, idea generation/validation and participating in several long discussions.
  - Tom Lane – for patch review and code rework
  - Korry – for extensive code review within EnterpriseDB
  - Dharmendra, Siva, Merlin – for testing correctness/performance
  - Florian, Gregory – for floating ideas
  - Denis, Bruce – for constant encouragement and making me rework HOT thrice ☺
  - Faiz, Hope – for excellent project management within EnterpriseDB
  - Nikhil – for hearing to all my stupid ideas and helping with initial work
- The list is so long that I must have missed few names – apologies and many thanks to them

Some Background - MVCC

- PostgreSQL uses MVCC (Multi Version Concurrency Control) for transaction semantics
- The good things:
  - Readers don't wait for writers
  - Writer doesn't wait for readers
  - Highly concurrent access and no locking overhead
- The bad things:
  - Multiple versions of a row are created
  - The older, dead versions can not be easily removed because indexes don't have visibility information
  - Maintenance overhead to reduce table/index bloat

MVCC - UPDATE

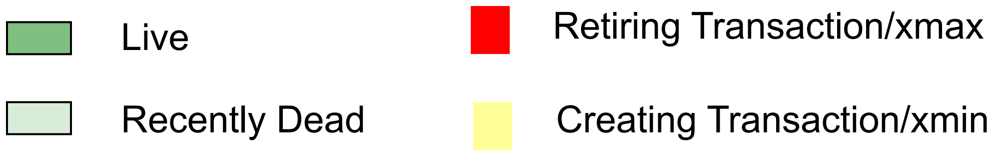


- Transaction T1 Updates V1
- Transaction T1 Commits

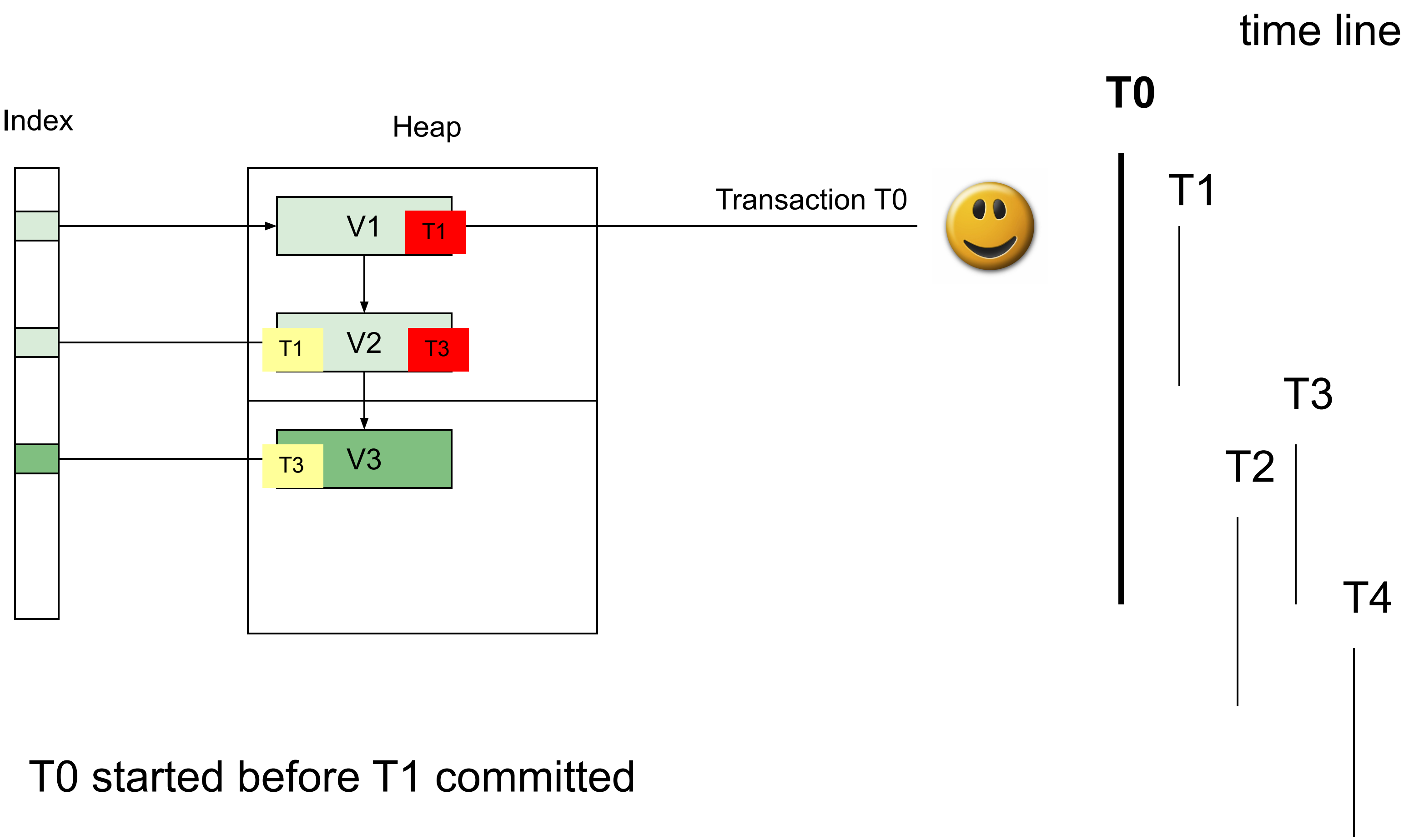
  V1 is dead, but still visible to older transactions, so we call it **RECENTLY DEAD**

- Transaction T3 Updates V2
- Transaction T3 Commits

  V2 is dead, but still visible to older transactions, It's also **RECENTLY DEAD**



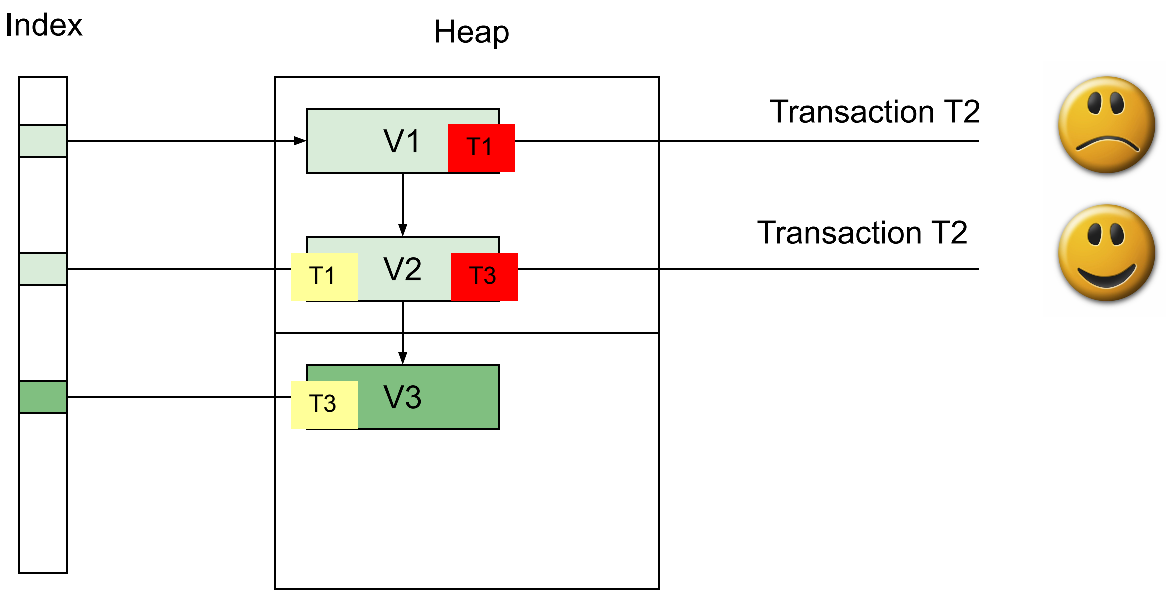
MVCC - Visibility

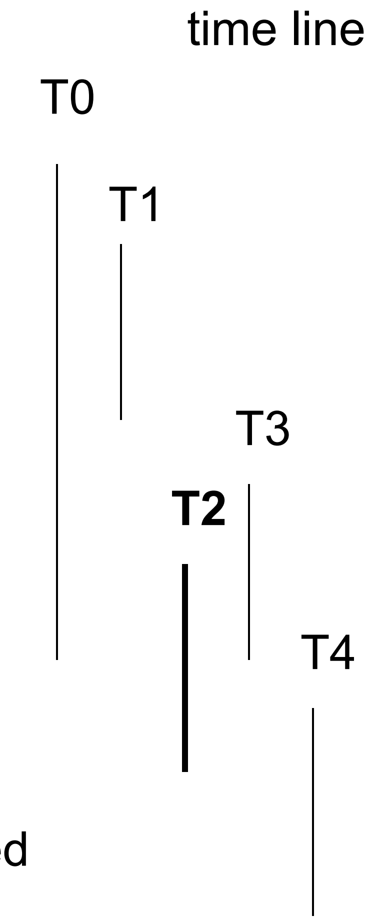


T0 started before T1 committed

T0 can only see V1

MVCC - Visibility

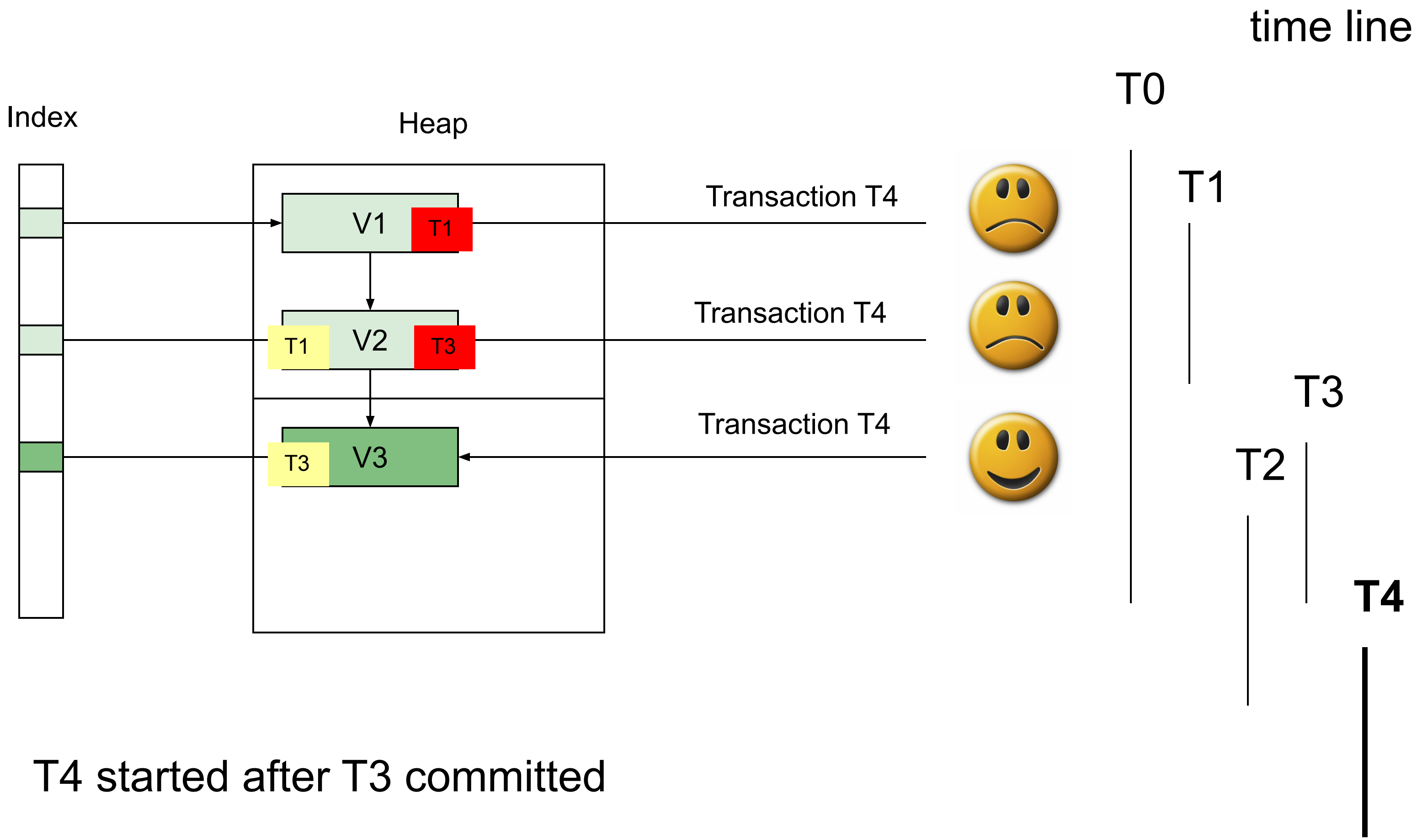




T2 started after T1 committed, but before T3 committed

T2 can only see V2

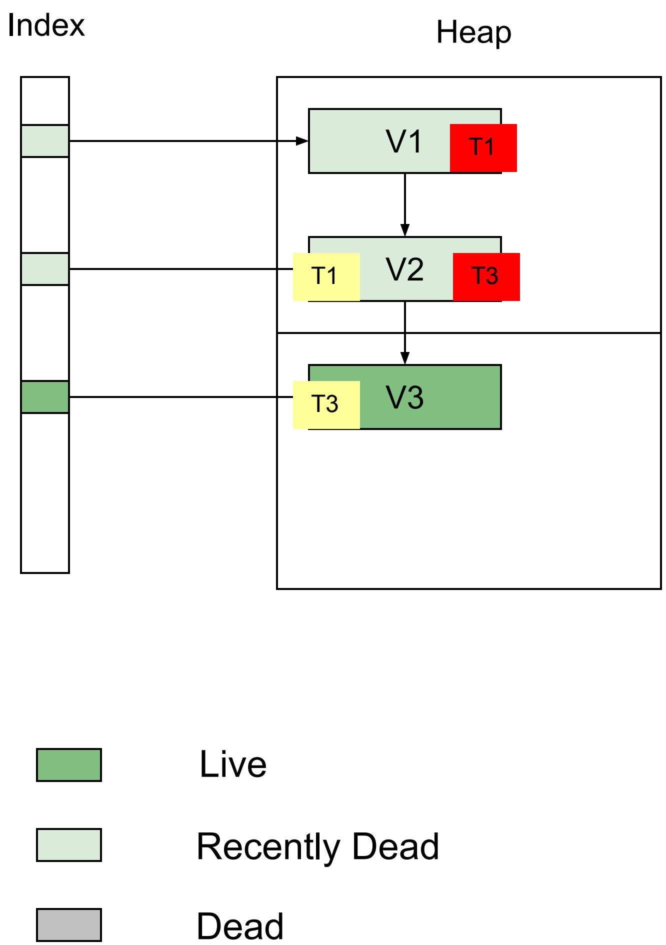
MVCC - Visibility



T4 started after T3 committed

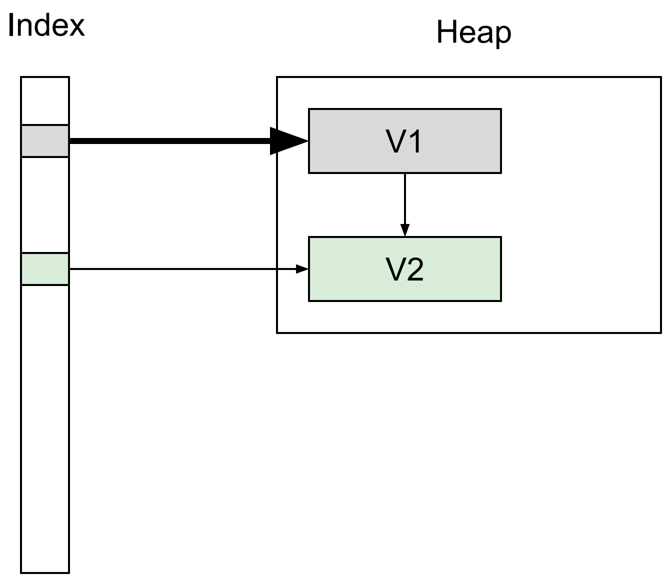
T4 can only see V3

MVCC – Tuple States



- V1 and V2 are **RECENTLY DEAD**, V3 is the most current and **LIVE** version
- V1 and V2 can not be removed, because T0 and T2 can still see them
- T0 finishes, V1 becomes **DEAD**
- T2 finishes, V2 becomes **DEAD**
- Only V3 remains **LIVE**

Removing DEAD Tuples

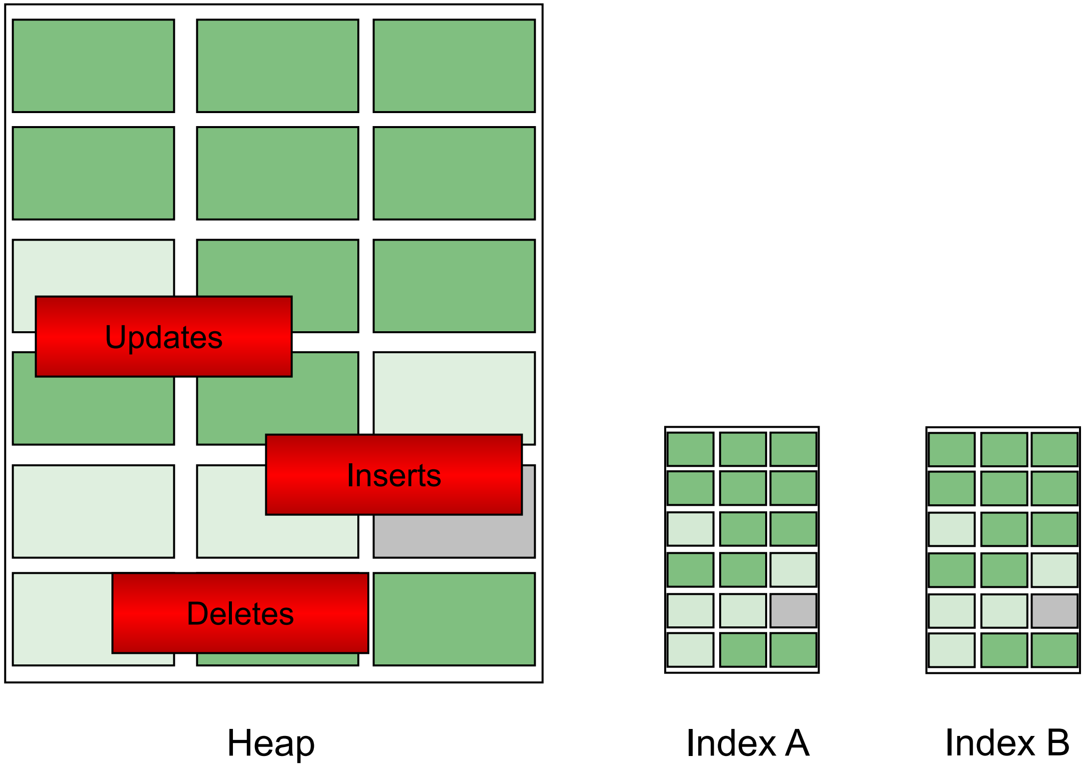


- V1 is DEAD. If it's removed, we would have a dangling pointer from the index.
- V1 can not be removed unless the index pointers pointing to it are also removed

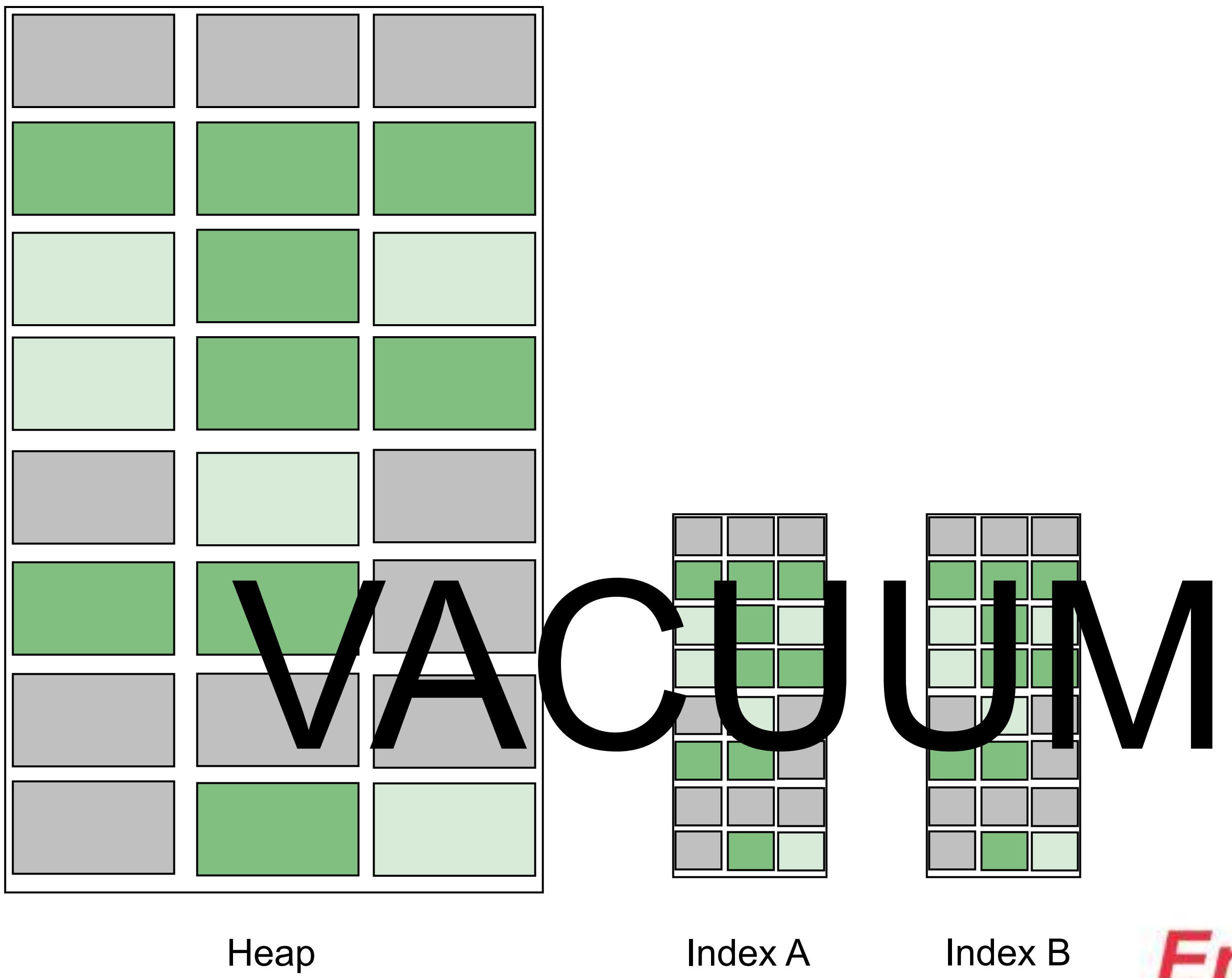
Note: Index entries do not have any visibility Information

- Near impossible to reliably find index pointers of a given tuple.

MVCC - Index/Heap Bloat



MVCC - Index/Heap Bloat



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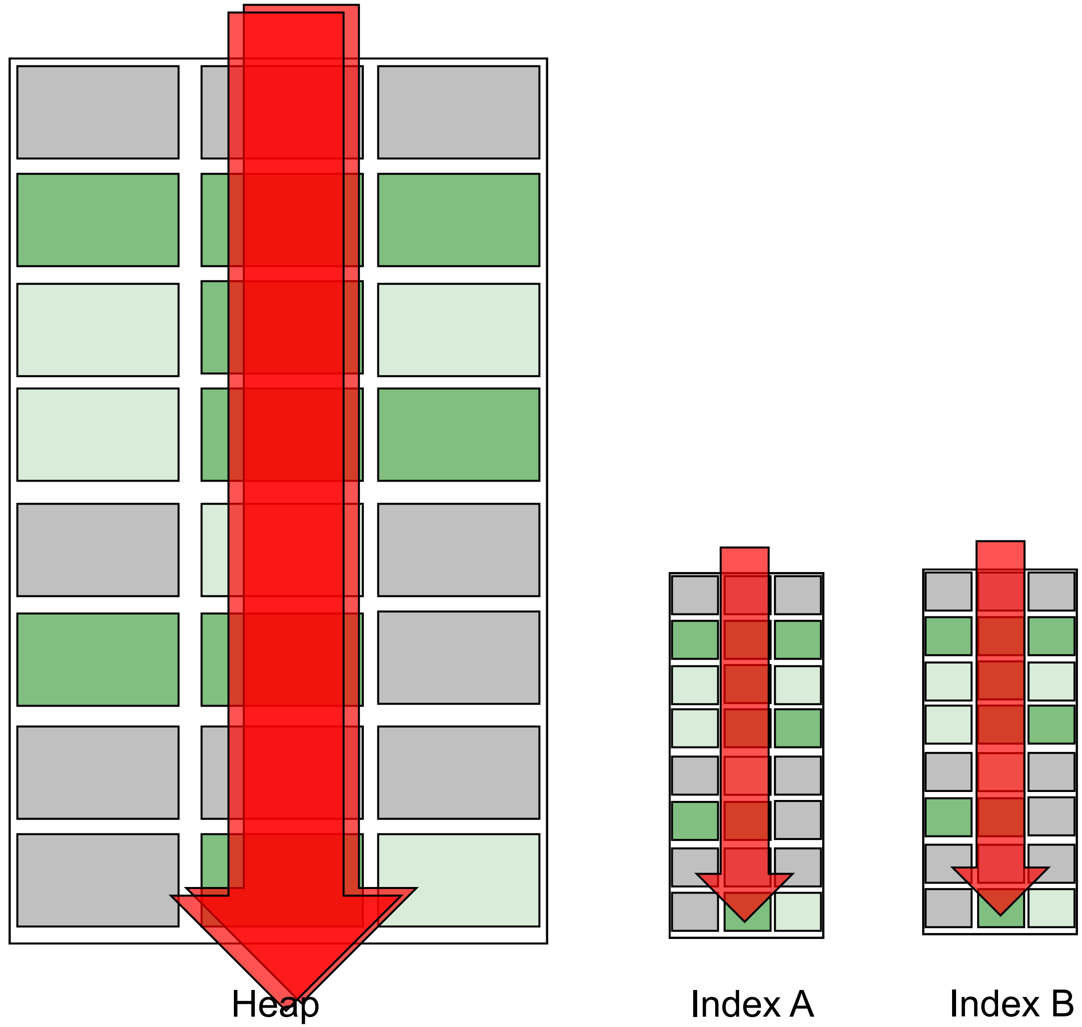
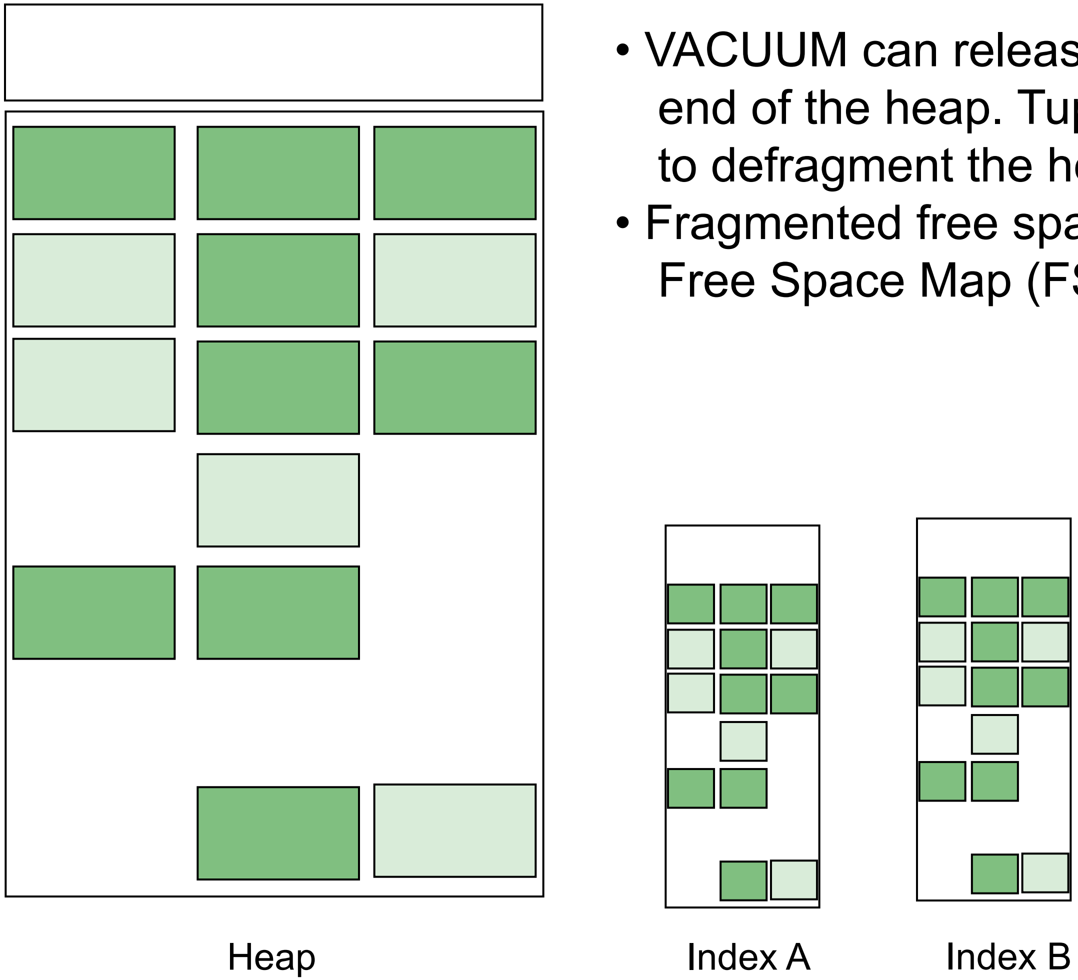
Vacuum – Two Phase Process



Vacuum

- VACUUM can release free space only at the end of the heap. Tuples are not reorganized to defragment the heap
- Fragmented free space is recorded in the Free Space Map (FSM)



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Motivation

- Frequent Updates and Deletes bloat the heap and indexes resulting in performance degradation in long term – spiral of death
- Each version of a row has it's own index entry, irrespective of whether index columns changed or not – index bloat
- Retail VACUUM is near impossible (dangling index pointers)
- Regular maintenance is required to keep heap/index bloat in check (VACUUM and VACUUM FULL)
  - Normal VACUUM may not shrink the heap, VACUUM FULL can but requires exclusive lock on the table
  - VACUUM requires two passes over the heap and one or more passes over each index.
  - VACUUM generates lots of IO activity and can impact the normal performance of the database.
  - Must be configured properly

Pgbench Results

- scale = 90, clients = 30, transactions/client = 1,000,000
- two CPU, dual core, 2 GB machine
- separate disks for data (3 disks RAID0) and WAL (1 disk)
- shared_buffers = 1536MB
- autovacuum = on
- autovacuum_naptime = 60
- autovacuum_vacuum_threshold = 500
- autovacuum_vacuum_scale_factor = 0.1
- autovacuum_vacuum_cost_delay = 10ms
- autovacuum_vacuum_cost_limit = -1

Heap Bloat (# blocks)

	Postgres 8.2		Postgres 8.3 Pre HOT		Postgres 8.3 Post HOT	
	Original Size	**Increase in Size**	Original Size	Increase in Size	Original Size	Increase in Size
Branches	1	**49,425**	1	**166**	1	**142**
Tellers	6	**18,080**	5	**1,021**	5	**171**
Accounts	155,173	**243,193**	147,541	**245,835**	147,541	**5,523**

In 8.2, the heap bloat is too much for small and large tables

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Postgres 8.3 – Multiple Autovacuum

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Multiple autovaccum processes helped small tables, but not large tables

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Postgres 8.3 – HOT (Retail Vacuum)

	Postgres 8.2		Postgres 8.3 Pre HOT		Postgres 8.3 Post HOT	
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Several Ideas

- Update In Place
  - The first design. Replace old version with the new version and move old version somewhere else
  - It was just too complicated!
- Heap Overflow Tuple
  - That's what HOT used to stand for
  - A separate overflow relation to store the old versions.
  - Later changed so that the new version goes into the overflow relation and pulled into the main relation when old version becomes dead.
  - Managing overflow relation and moving tuples around was painful.
- Heap Only Tuple
  - That's what HOT stands for today
  - Tuples without index pointers

HOT Update

Necessary Condition A: *UPDATE does not change any of the index keys*

Example:

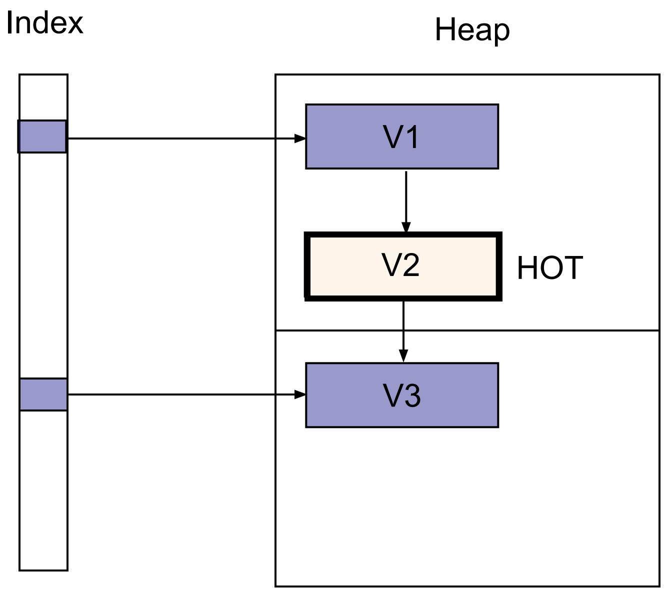
```
CREATE TABLE test (a int, b char(20));
CREATE UNIQUE INDEX textindx ON test(a);
INSERT INTO test VALUES (1, ‘foo’);

UPDATE test SET b = ‘bar’ WHERE a = 1;
UPDATE test SET a = a + 1 WHERE a = 1;
```

First UPDATE changes the non-index column – candidate for HOT update

Second UPDATE changes the index column – HOT update not possible

HOT Update



- V1 is updated – no index key change
  Single Index Entry Update Chain

- V2 is updated – no free space in block

Necessary Condition B*: The new version should fit in the same old block – HOT chains can not cross block boundary.*

HOT Update – Necessary Conditions

Necessary Condition A: *UPDATE does not change any of the index keys*

Necessary Condition B*: The new version should fit in the same old block – HOT chains can not cross block boundary.*

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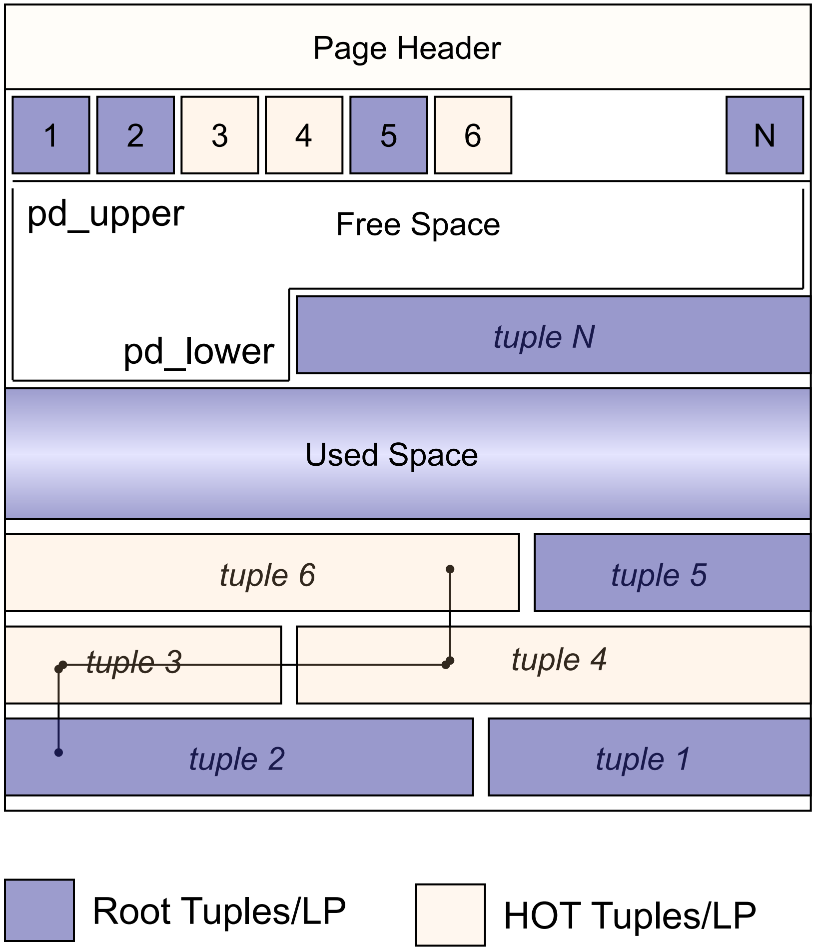
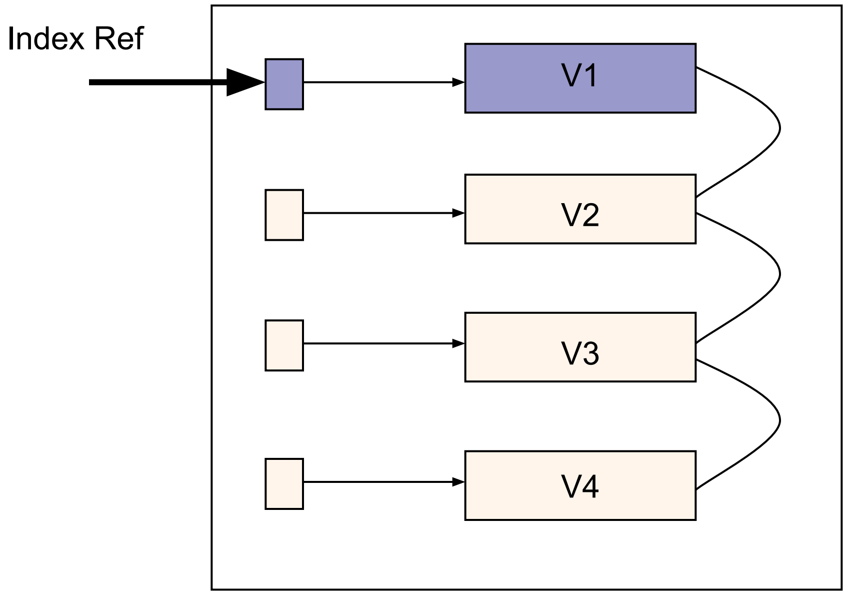
Inside A Block



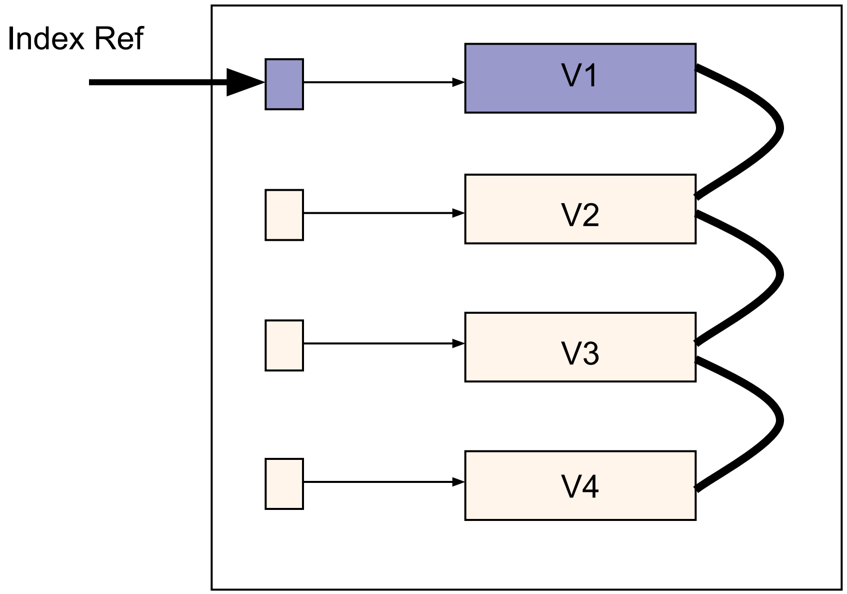
- Page Header followed by line pointers
- Line pointers point to the actual tuples
- Indexes always point to the line pointers and not to the actual tuple
- HOT chains originate at Root LP and may have one or more HOT tuples
- **HOT tuples are not referenced by the indexes directly.**

HOT – Heap Scan



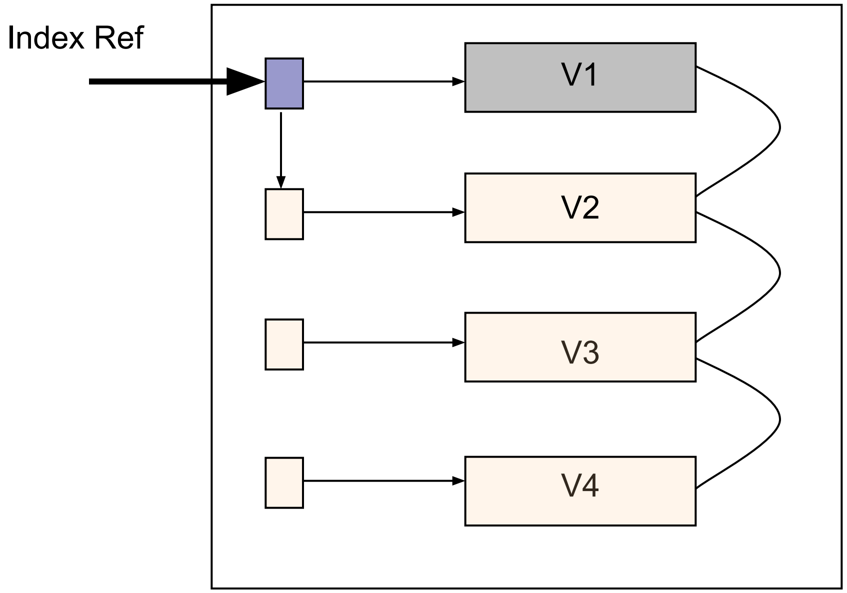
- No change to Heap Scan
- Each tuple is examined separately and sequentially to check if it satisfies the transaction snapshot

HOT – Index Scan



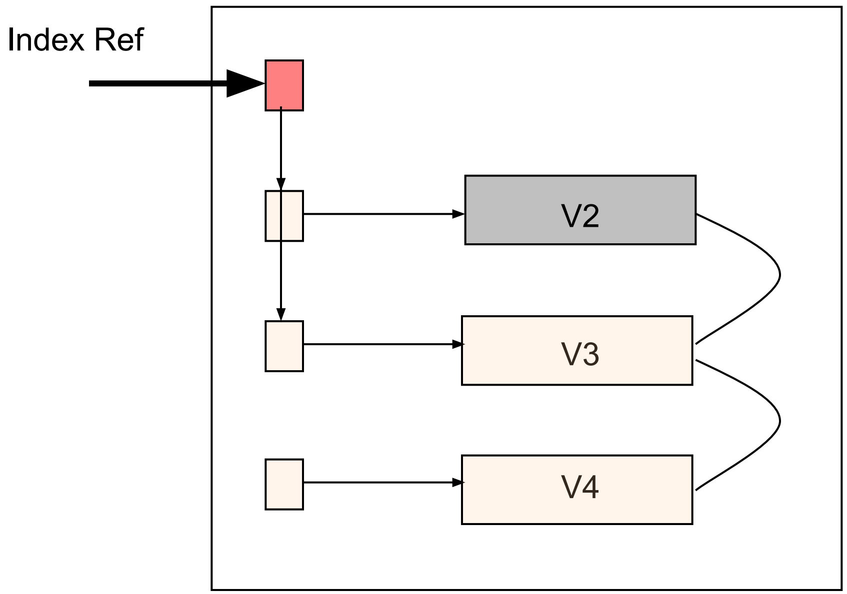
- Index points to the Root Tuple
- If the Root tuple does not satisfy the snapshot, the next tuple in the HOT chain is checked.
- Continue till end of the HOT chain
- The Root tuple can not be removed even if it becomes DEAD because index scan needs it

Pruning – Shortening the HOT Chain



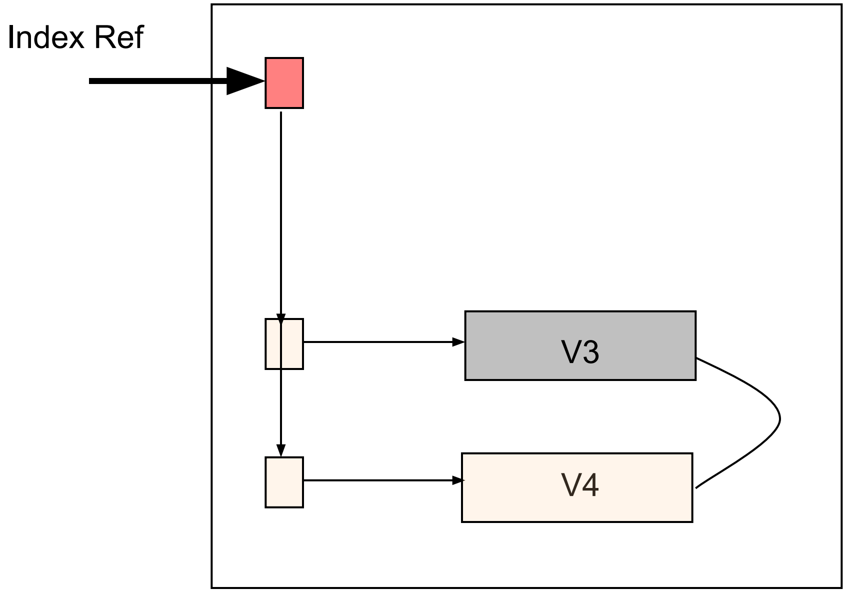
- V1 becomes DEAD
- V1 is removed, but it’s line pointer (LP) can not be removed – index points to it
- Root LP is redirected to the LP of next tuple in the chain

Pruning – Shortening the HOT Chain



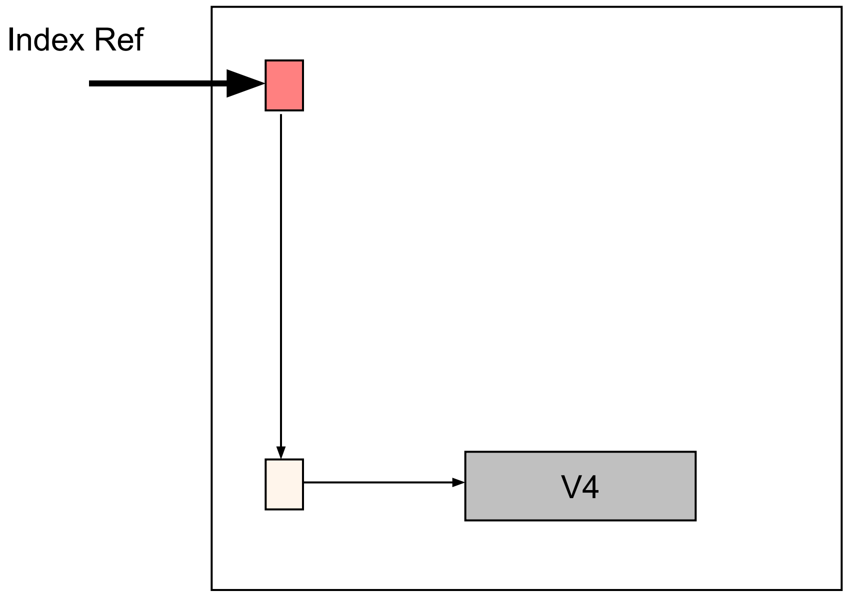
- Root LP is a redirected LP
- V2 becomes DEAD
- V2 and it's LP is removed – HOT tuple
- Root LP now redirects to the next tuple in the chain

Pruning – Shortening the HOT Chain



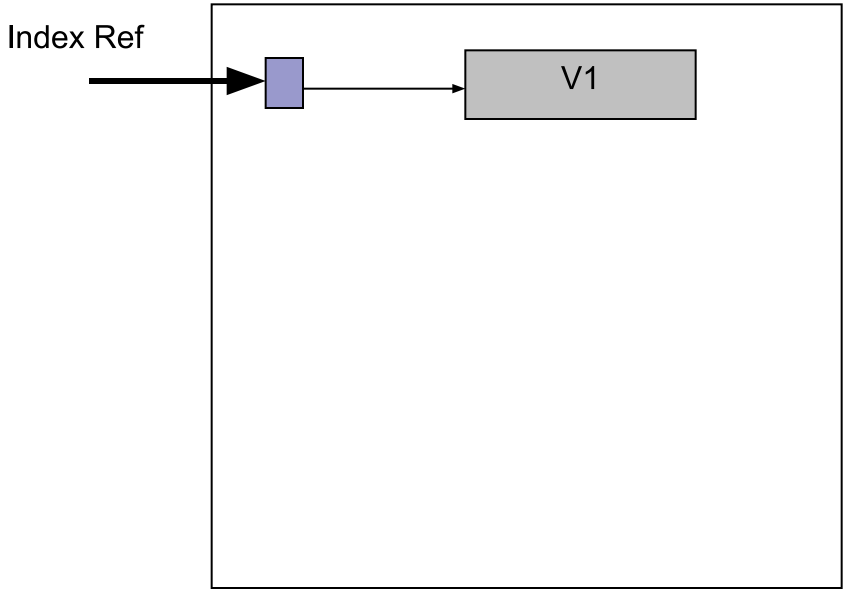
- Root LP is a redirected LP
- V3 becomes DEAD
- V3 and it’s LP is removed – HOT tuple
- Root LP now redirects to the next tuple in the chain

Pruning – Shortening the HOT Chain



- Root LP is a redirected LP
- V4 becomes DEAD
- V4 and it's LP is removed – HOT tuple
- Root LP is now DEAD – still can't be removed

Pruning – Normal UPDATEs and DELETEs



- Normal UPDATEd and DELETEd tuples are removed and their LPs are marked DEAD – LPs can't be removed
- A very useful side-effect of HOT

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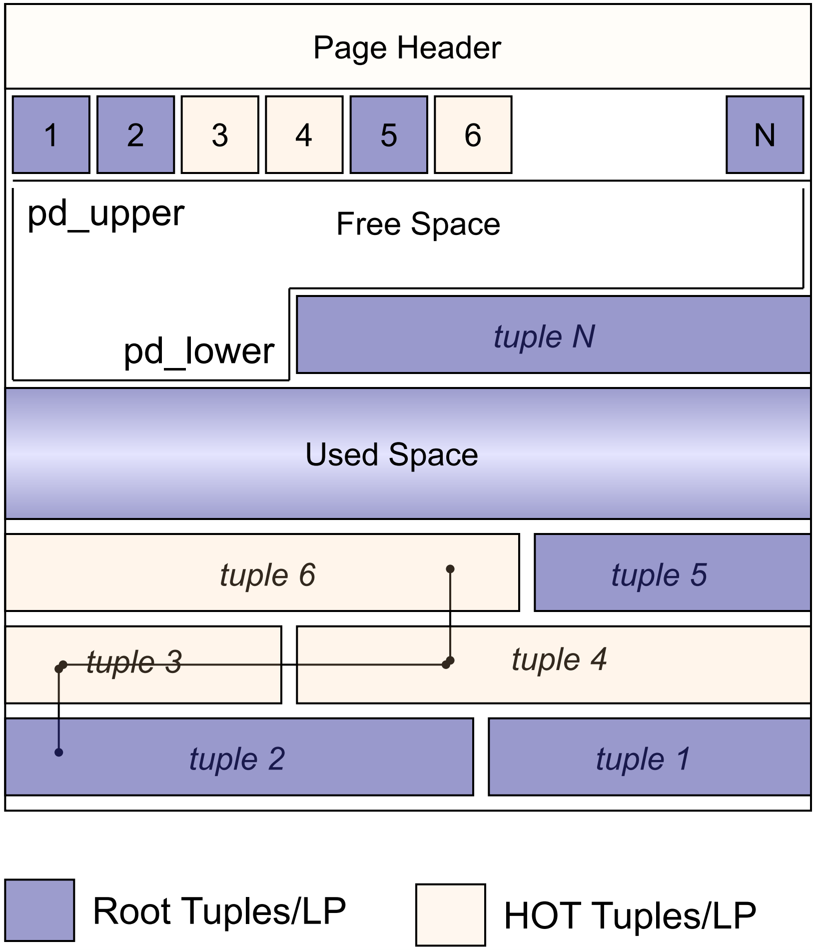
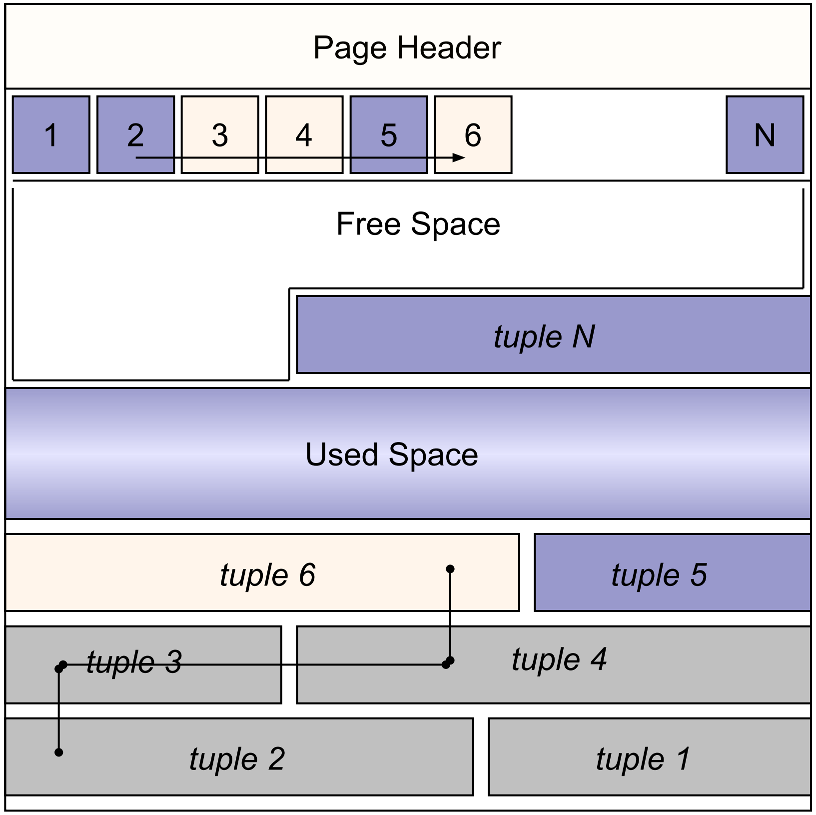
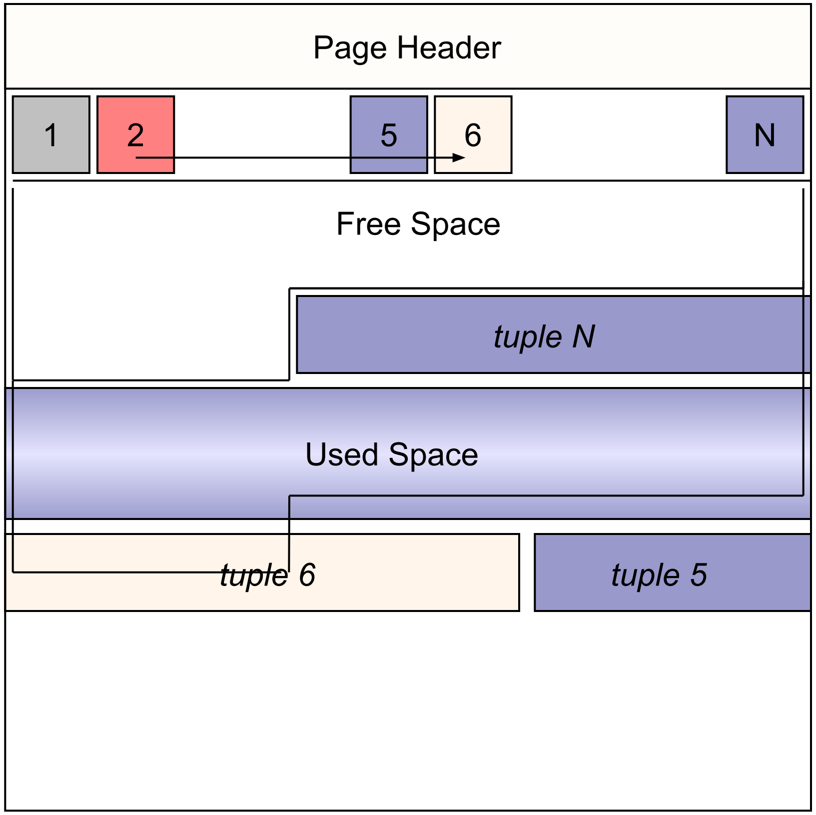
Pruning and Defragmentation



Pruning – Recovering Dead Space



Defragmentation – Collecting Dead Space



Billion $ Question – When to Prune/Defragment ?

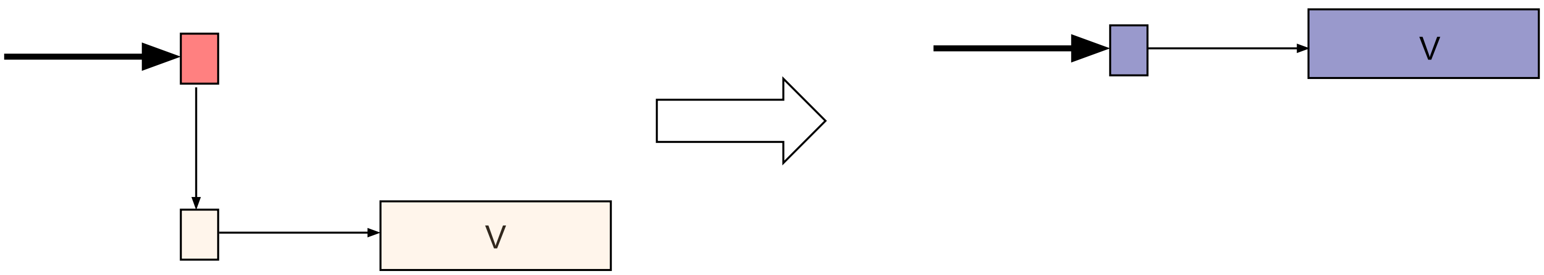
- Pruning and defragmentation (PD) happens together – requires cleanup lock on the buffer and shuffles tuples in a page.
- Too frequent PD may conflict with other backends accessing the buffer.
- Too infrequent PD may slow down reclaiming dead space and create long HOT chains.
- Page level hint bits and transaction id is used to optimize PD operations.

Page Level Hints and Xid

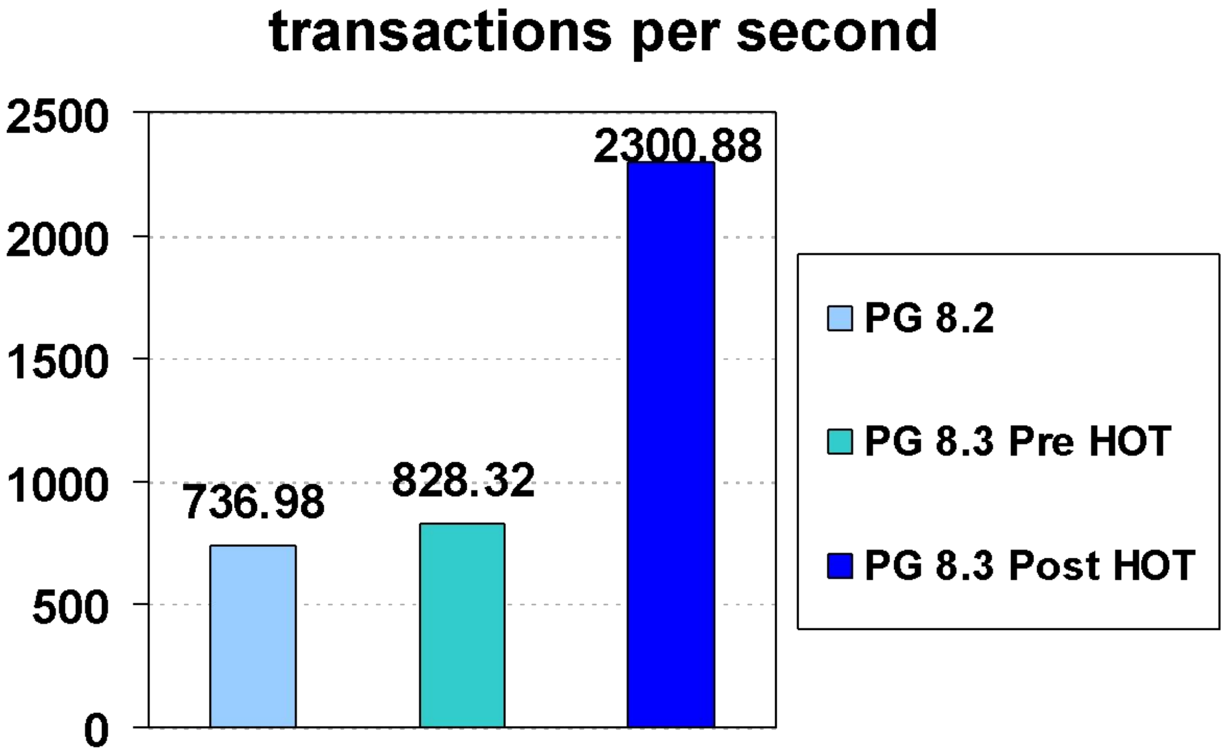
- If UPDATE does not find enough free space in a page, it does COLD UPDATE but sets PD_PAGE_FULL flag
- The next access to page may trigger prune/defrag operation if cleanup lock is available.
- PD never waits for cleanup lock
- Page Xid is set to the oldest transaction id which deleted or updated a tuple in the page. PD is usable only if RecentGlobalXmin is less than the Page Xid.

Lazy Vacuum / Vacuum Full

- Lazy Vacuum is almost unchanged.
- DEAD line pointers are collected and reclaimed.
- Vacuum Full clears the redirected line pointers by making them directly point to the first visible tuple in the chain.



Headline Numbers - Comparing TPS



That's a good 200% increase in TPS

Comparing Heap Bloat (# blocks)

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HOT significantly reduces heap bloat; for small and large tables

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Comparing Index Bloat (# blocks)

	Postgres 8.2		Postgres 8.3 Pre HOT		Postgres 8.3 Post HOT	
	Original Size	**Increase in Size**	Original Size	**Increase in Size**	Original Size	**Increase in Size**
Branches	2	**1,023**	2	**588**	2	**4**
Tellers	5	**353**	5	**586**	5	**19**
Accounts	24,680	**24,679**	24,680	**24,677**	24,680	**0**

HOT significantly reduces index bloat too; for small and large tables

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Comparing IO Stats

		Postgres 8.2		Postgres 8.3 Pre HOT		Postgres 8.3 Post HOT	
		Blks Read	Blks Hit	Blks Read	Blks Hit	Blks Read	Blks Hit
Branches	H	576,949	810,688,147	8,595	2,904,470,056	784	74,640,567
	I	7,540	330,165,668	68,992	254,298,111	7	56,184,941
Tellers	H	685,599	219,033,182	7,710	452,528,173	678	62,275,473
	I	366	135,684,700	599	210,984,757	28	60,655,207
Accounts	H	20,138,195	167,902,036	19,065,032	173,465,111	162,867	101,354,726
	I	464,641	266,747,533	482,835	270,662,463	49,327	181,307,038

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	I	464,641	266,747,533	482,835	270,662,463	49,327	181,307,038

Significant reduction in IO improves the headline numbers

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What Should I Do ?

- Nothing! HOT is always enabled and there is no way to disable it.
- It works on user and system tables
- A heap fill factor less than 100 may help
- A significantly smaller heap fill factor (as low as 50) is useful for heavy updates where most of the updates are bulk updates
- Non index key updates is a necessary condition for HOT – check if you don't need one of the indexes.
- Prune-defrag reclaims COLD UPDATEd and DELETEd DEAD tuples by converting their line pointers to DEAD
- You still need VACUUM – may be less aggressive

Limitations

- Free space released by defragmentation can only be used for subsequent UPDATEs in the same page – we don't update FSM after prune-defragmentation
- HOT chains can not cross block boundaries
- Newly created index may remain unusable for concurrent transactions
- Normal vacuum can not clean redirected line pointers

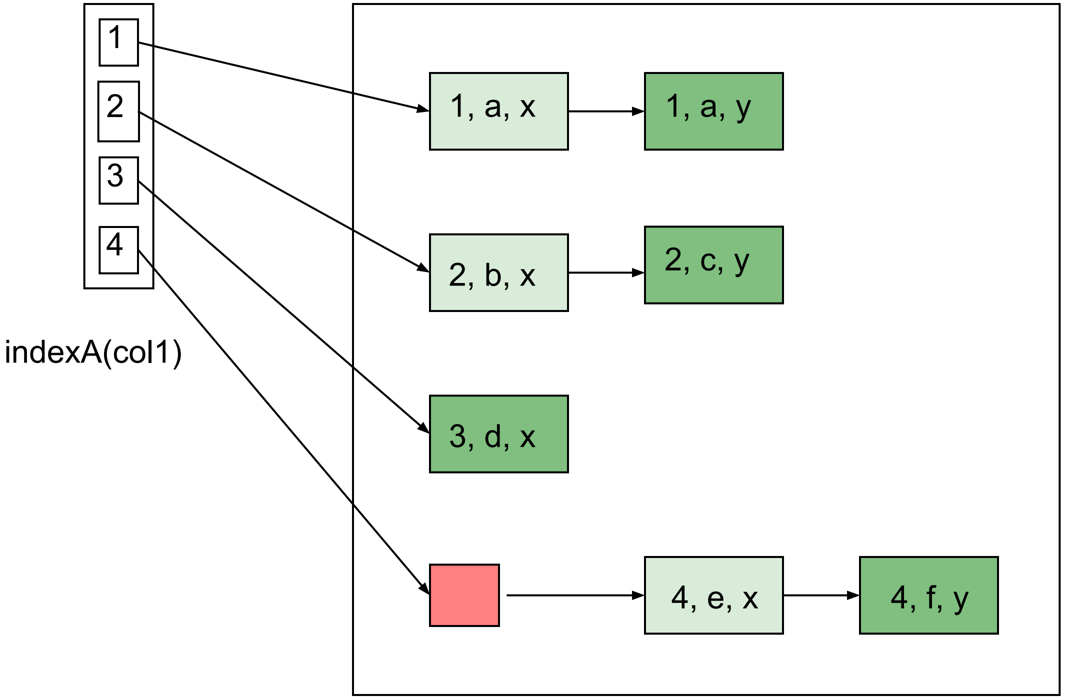
Create Index

- This was one of the most interesting challenges in HOT development.
- The goal was to support CREATE INDEX without much or no impact on the existing semantics.
- Did we succeed ? Well, almost

Create Index - Challenges

- Handling broken HOT chains
- New Index must satisfy HOT properties
  - All tuples in a HOT chain must share the same index key
  - Index should not directly point to a HOT tuple.
- Create Index should work with a ShareLock on the relation

Create Index – Sane State

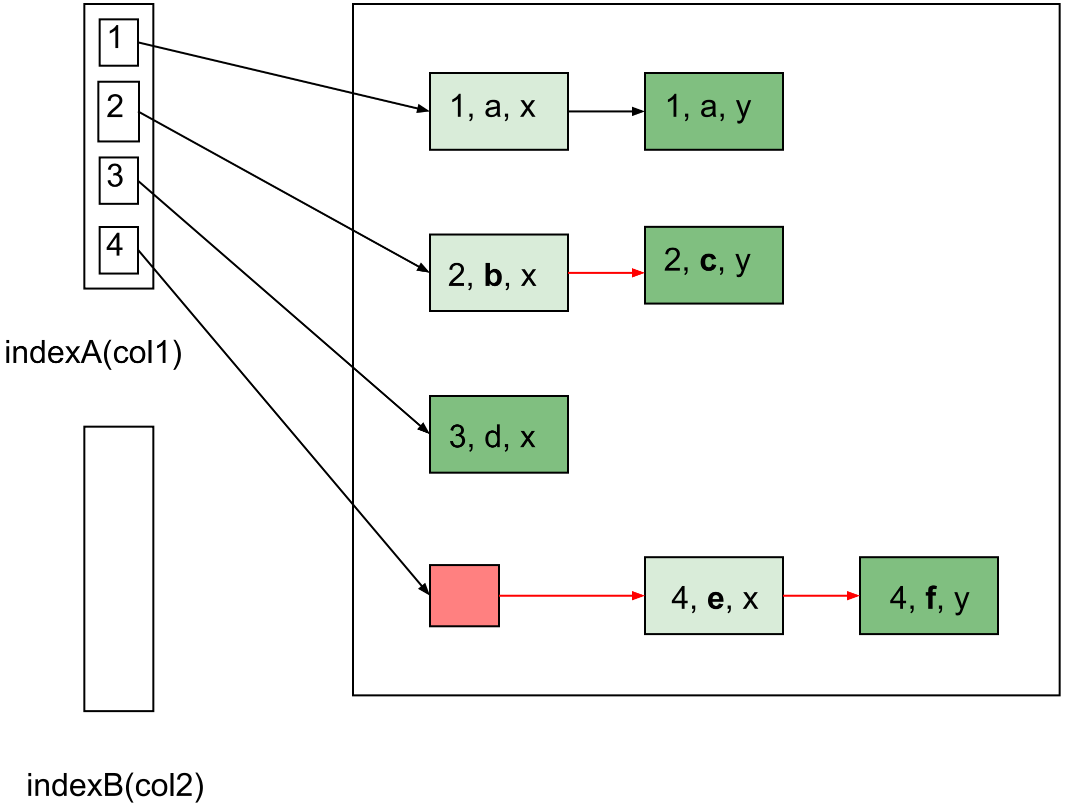


- All HOT chains are in sane state
- Every tuple in a chain shares the same index key
- Index points to the Root Line Pointer

Create Table test (col1 int, col2 char, col3 char);

Create Index indexA ON test(col1);

Create Index – Broken HOT Chains



- **Create a new Index on col2**
- Second and fourth HOT chains, marked with → , are broken w. r. t. new Index
- tuples are recently dead, but may be visible to concurrent txns

Create Index indexB ON test(col2);

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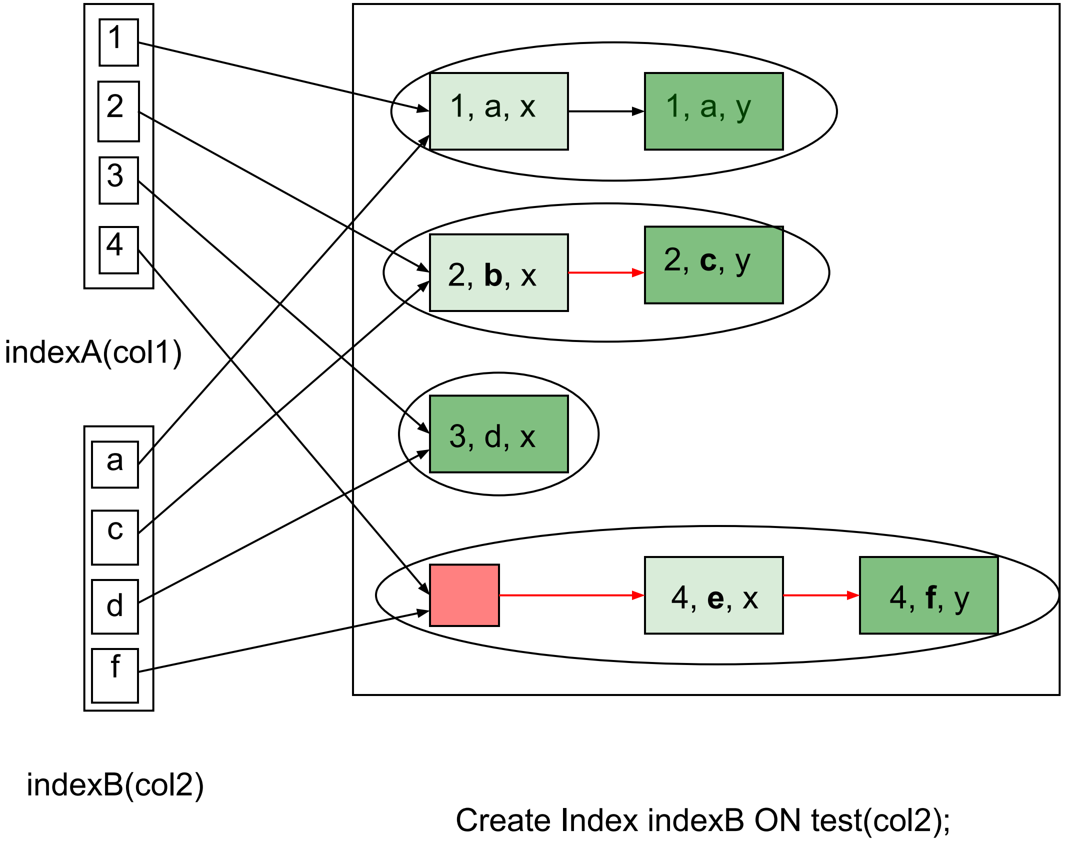
Create Index – Building Index with Broken HOT Chains



- Recently Dead tuples are not indexed
- Index remains unusable to the transactions which can potentially see these skipped tuples, including the transaction which creates the index
- Any new transaction can use the index
- xmin of pg_class row is used to check index visibility for transactions

Thank you

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