Microsoft

SQL Server Index Structure

Module 5

Learning Units covered in this Module

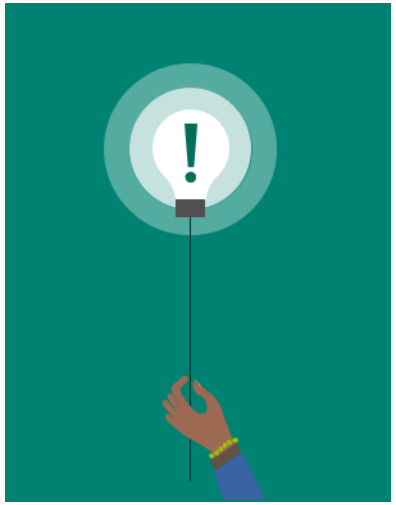
- Lesson 1: Index Internals
- Lesson 2: Index Strategy
- Lesson 3: Partitioned Tables and Indexes
- Lesson 5: Index Monitoring and Fragmentation
- Lesson 4: Columnstore Indexes
- Lesson 6: In-Memory Tables

Lesson 1: Index Internals

Objectives

After completing this learning, you will be able to:

- Understand differences between heap and clustered objects.
- Describe B-Trees, and why they are beneficial.
- Understand the differences between clustered and non-clustered indexes.
- Describe the different methods by which data structures are accessed.



What is an Index?

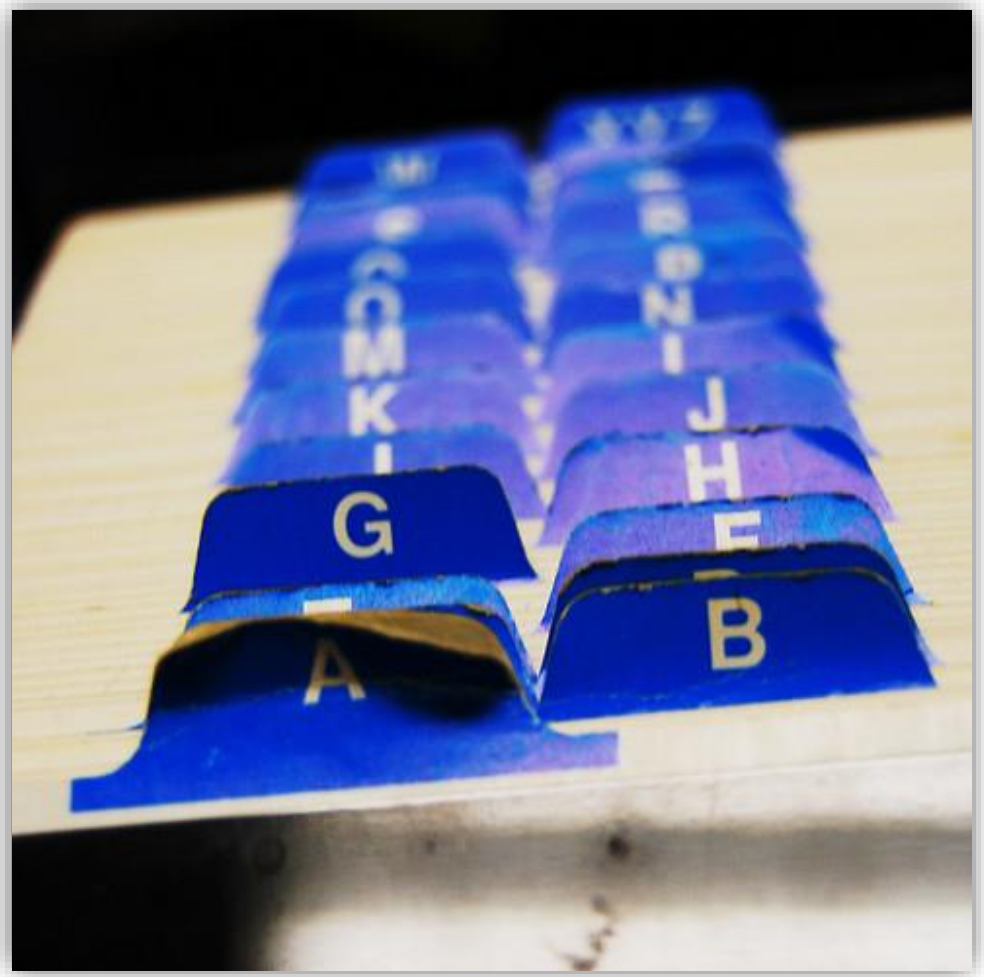
An index is an on-disk structure associated with a table that speeds retrieval of rows.

An index contains keys built from one or more columns in the table.

What is SARGability?

A SARGable item in a search predicate is able to use an index.

Non-SARGable expressions can significantly slow down queries.



How Data is Stored in Data Pages

Data stored in a Heap is not stored in any order and normally does not have a Primary Key.

Heap

AcctID	AcctName	Balance
1	Jack	500.00
2	Diane	750.00
29	Kelli	1250.00
27	Jessica	1005.00
18	Maddison	745.00
22	Bella	445.00

Clustered Index data is stored in sorted order by the Clustering key. In many cases, this is the same value as the Primary Key.

Clustered Index

AcctID	AcctName	Balance
1	Jack	500.00
2	Diane	750.00
12	Danny	630.00
14	Mayleigh	204.00
15	Molly	790.00
18	Maddison	745.00

Heap

A heap is a table without a clustered index

Unordered masses of data

Can be good for quickly importing large sets of data

Not a good idea for reporting-based data structures

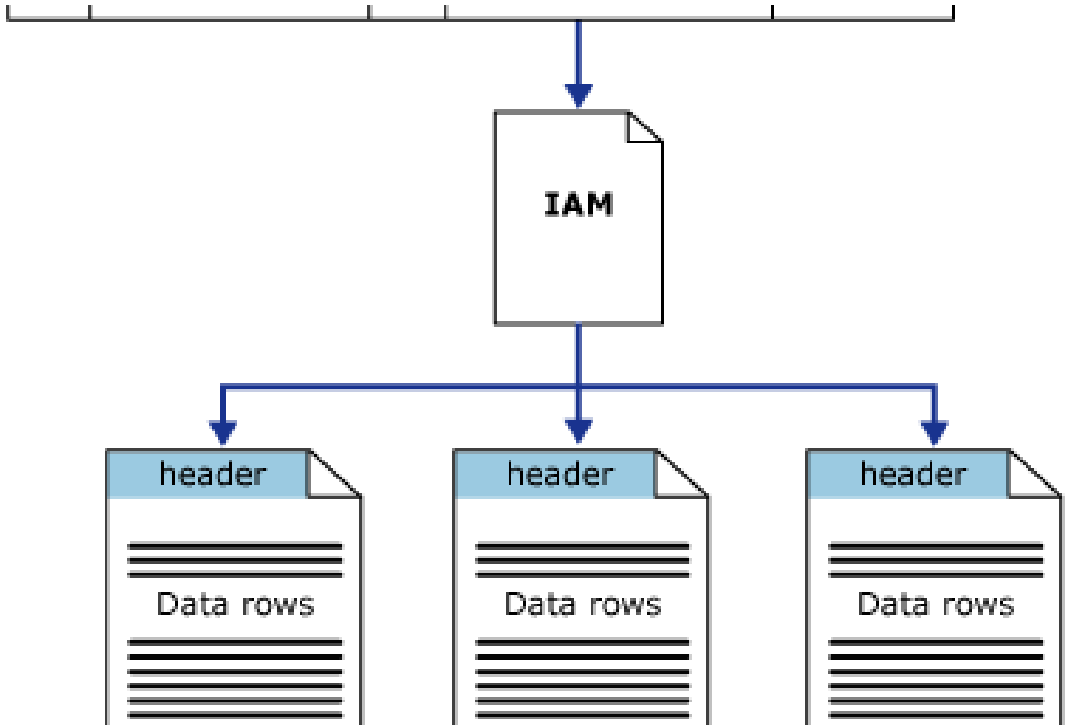
Use the ALTER TABLE…REBUILD command to “rebuild” a heap table

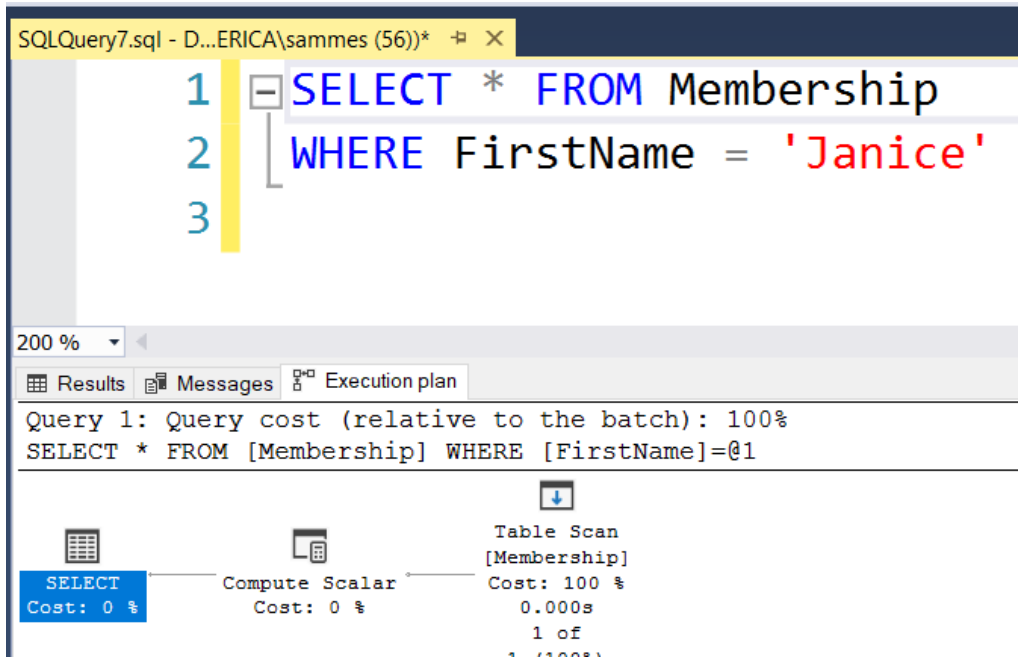
Do not use a heap

- When the data is frequently returned in a sorted order.
- When the data is frequently grouped together.
- When ranges of data are frequently queried from the table.
- When there are no nonclustered indexes and the table is large.

Heap Structures

Heaps have one row in sys.partitions, with index_id = 0 for each partition used by the heap





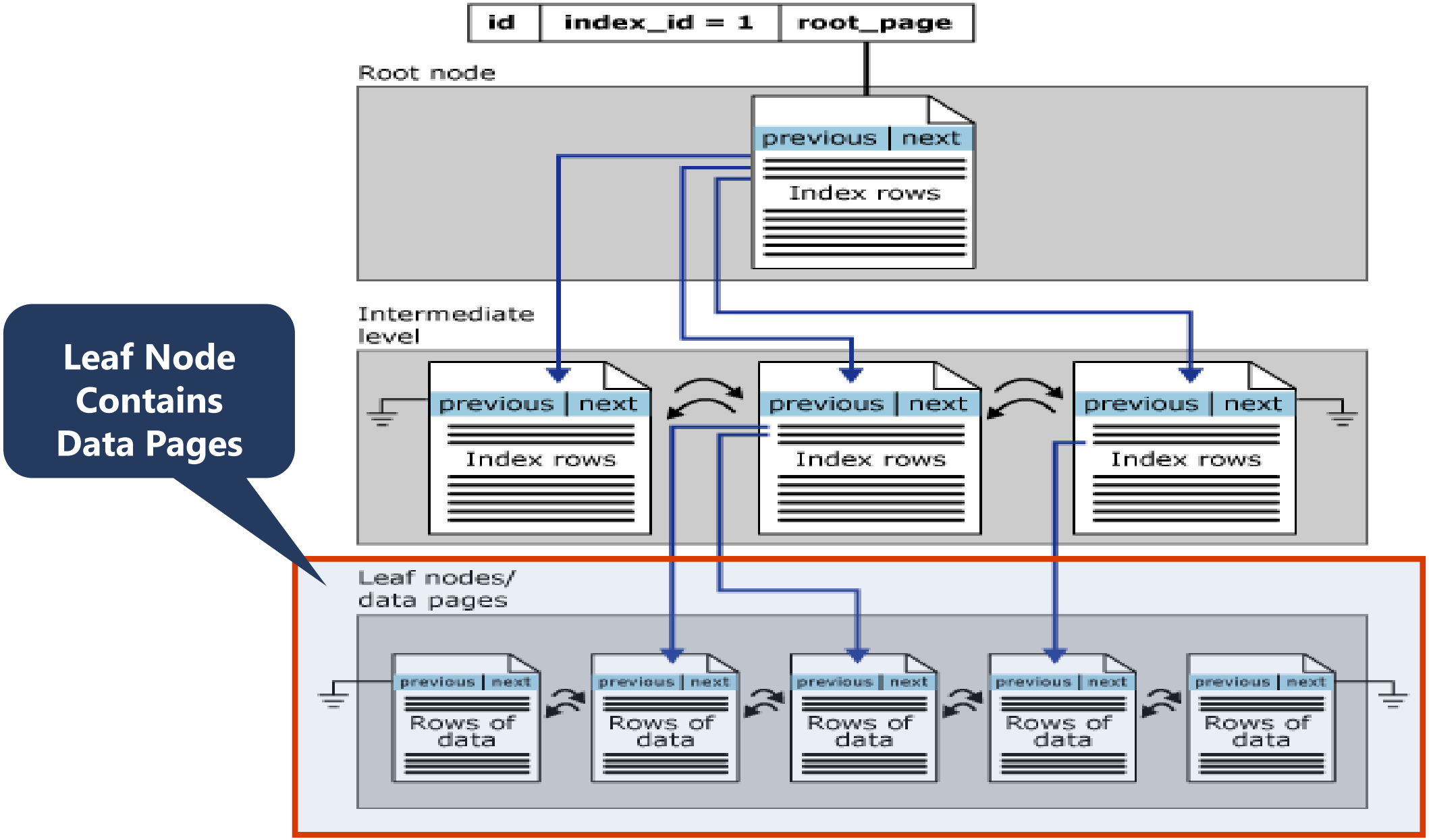
Clustered Indexes

An ordered data structure that is implemented as a Balanced (B) Tree.

When a table is clustered, the leaf level of the index contains ALL data in the table. This means that the clustered index IS the table. This is also why there is only one per table.

The leaf level of the clustered index contains data pages.

Clustered Index Structure



Demonstration

Examining index metadata and Building a B-Tree

- This demonstration reviews index, partition, and allocation unit metadata.
- Show how a B-Tree begins to form as rows are added to a table.

Non-Clustered Indexes

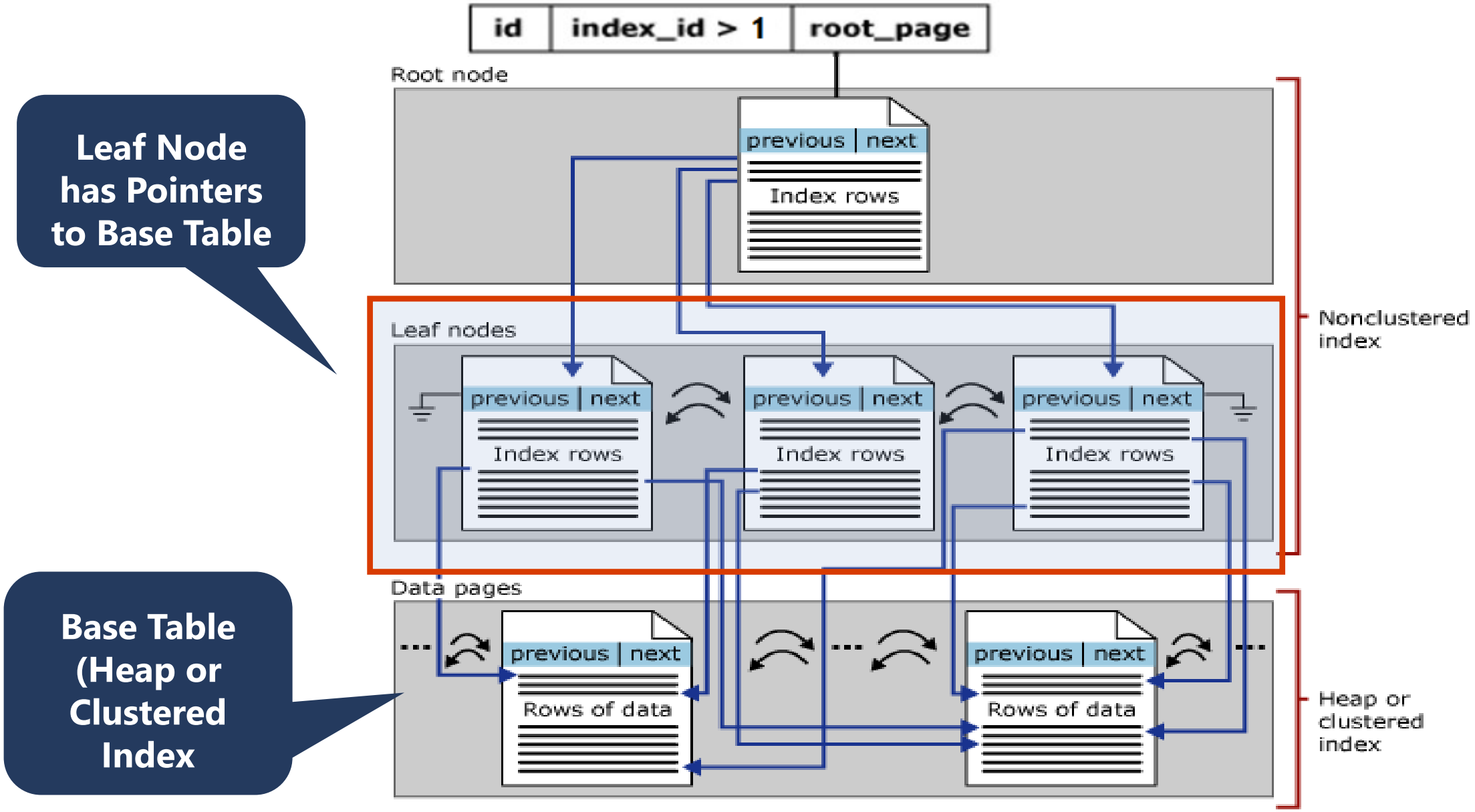
Same B-tree data structure as a clustered index.

It is a separate structure built on top of a Heap or Clustered Index.

Only contains a subset of the columns in the base table

The leaf level contains only the columns defined in the index as well as the clustered key/heap ID that points to the base table structure.

Non-Clustered Index Structure



Clustered vs Nonclustered Indexes

An index is an on-disk structure associated with a table or view that speeds retrieval of rows.

Clustered Indexes

- Defines the order in which data is physically stored in a table.
- Table data can be sorted in only one way.
- Leaf level has data rows stored with index.
- When a table has a clustered index, the object is called clustered table.
- Cluster key is added to nonclustered index (as the pointer), keep it as narrow as possible.

Non-clustered Indexes

- Separate structure from base table.
- Contains a pointer back to base table called:
  - Row ID (RID when base table is HEAP)
  - Key (KEY when base table is Clustered)
- "Skinny" data structure as it contains a subset of base table only.
- To by-pass index key limits (1,700 bytes) ,non-key columns can be added to leaf level.
- As Leaf level contains fewer columns than base table, the non-clustered index uses fewer pages than the corresponding base table.

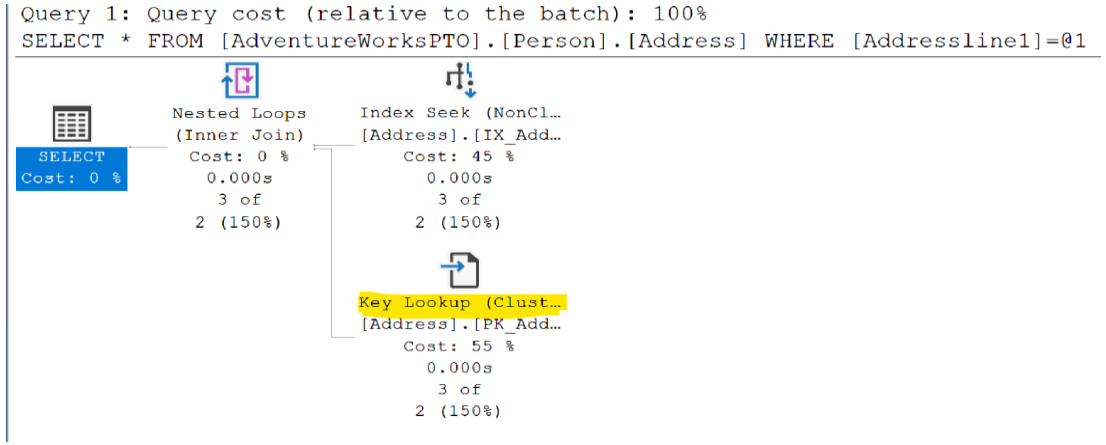
Bookmark Lookup or RID lookup

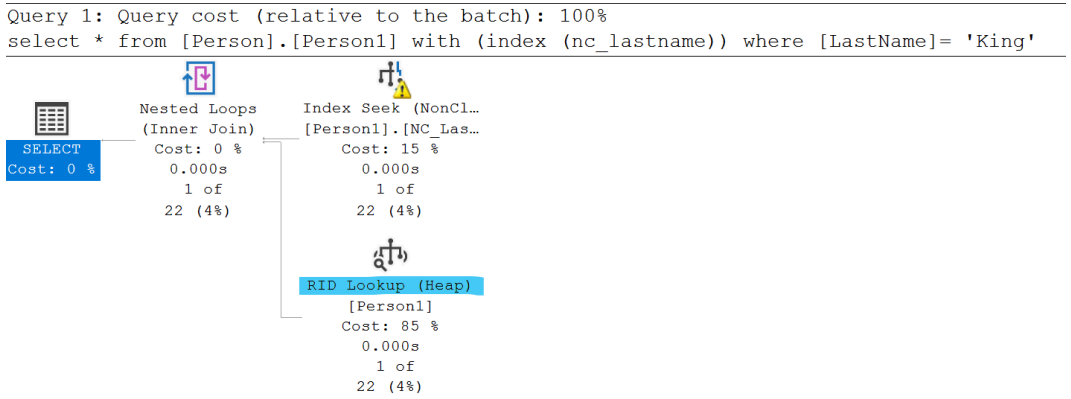
Occurs when SQL uses a nonclustered index to satisfy all or some of a query's predicates, but it doesn't contain all the information needed to cover the query.

Lookup effectively join the nonclustered index back to the clustered index or heap.

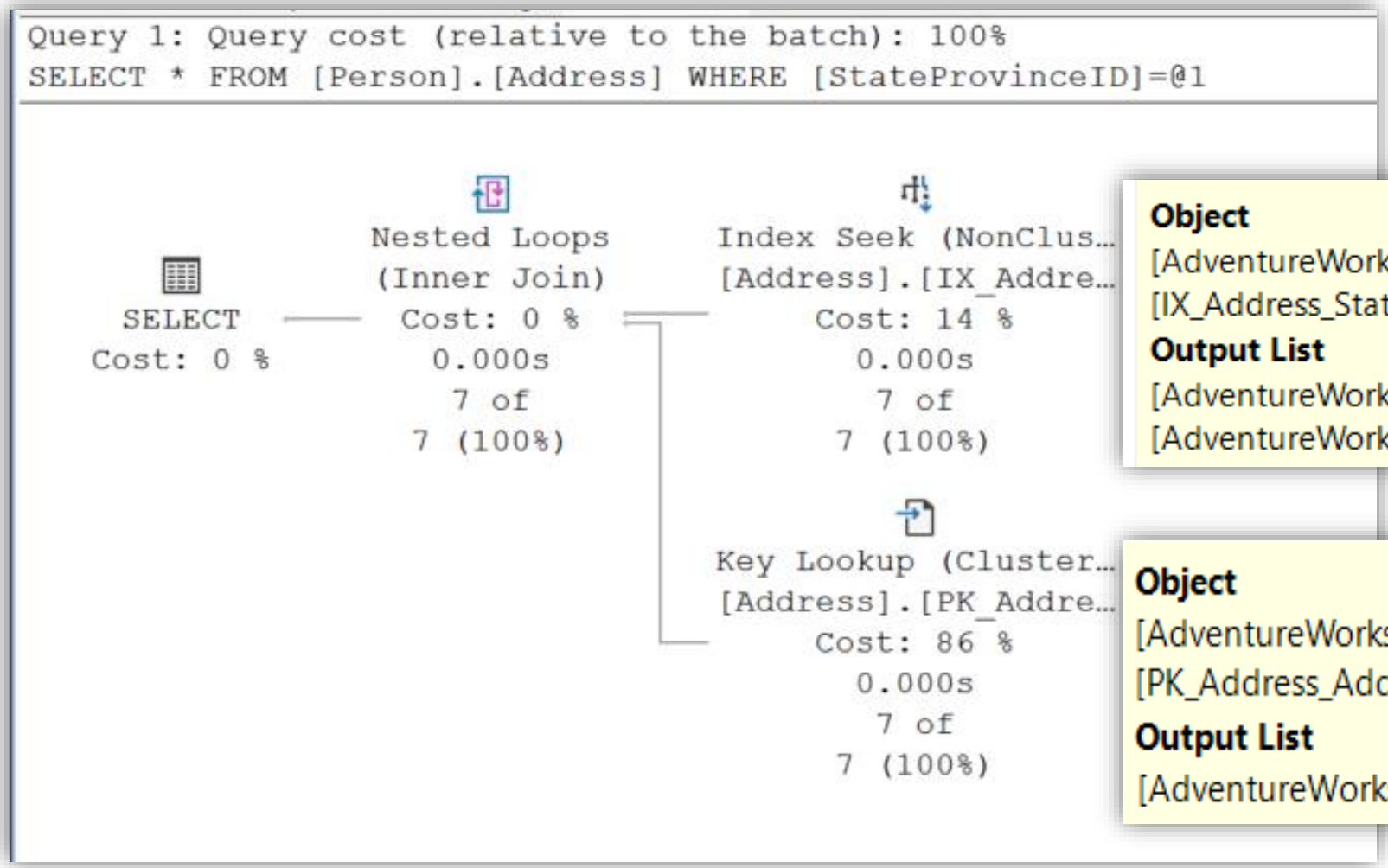
- If table has clustered index, it is called **bookmark lookup** (or key lookup)
- If the table is a heap with a non-clustered index, it is called **RID lookup**

This is an expensive operation.

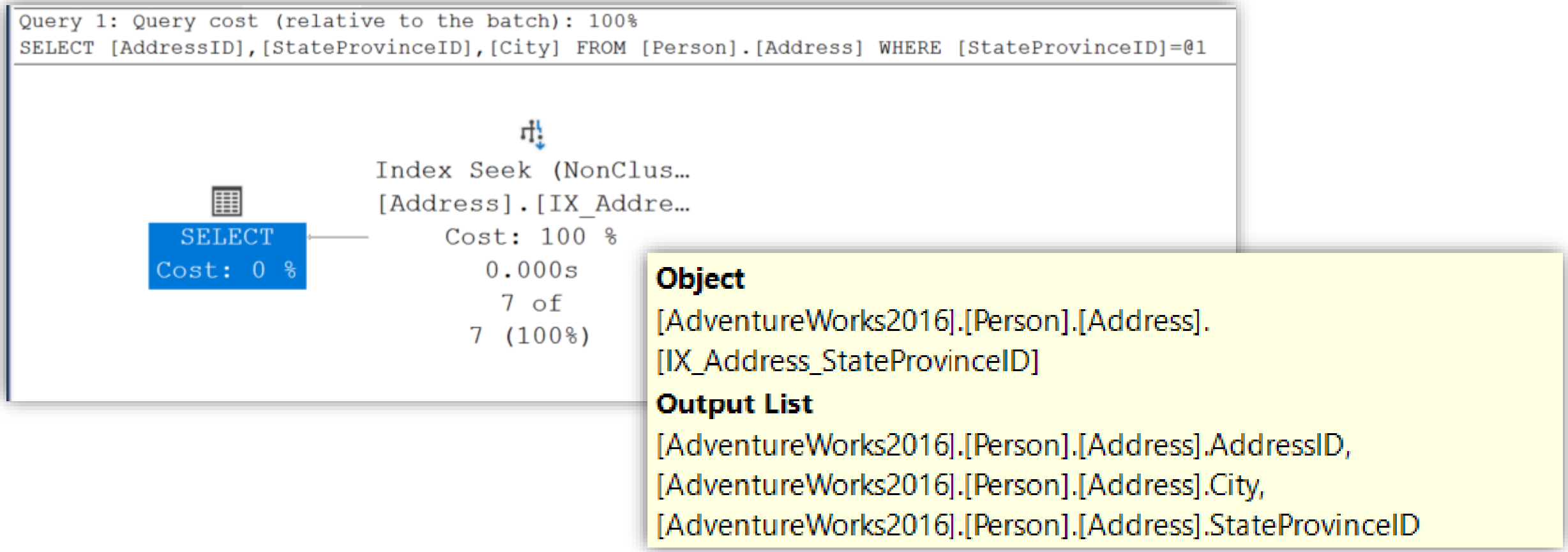




Key Lookup


Query 1: Query cost (relative to the batch): 100%
SELECT * FROM [Person].[Address] WHERE [StateProvinceID]=@1
SELECT
Cost: 0 %
Nested Loops
(Inner Join)
Cost: 0 %
0.000s
7 of
7 (100%)
Index Seek (NonClus…
[Address].[IX_Addre…
Cost: 14 %
0.000s
7 of
7 (100%)
Key Lookup (Cluster…
[Address].[PK_Addre…
Cost: 86 %
0.000s
7 of
7 (100%)
Object
[AdventureWorks2016].[Person].[Address].
[IX_Address_StateProvinceID]
Output List
[AdventureWorks2016].[Person].[Address].AddressID,
[AdventureWorks2016].[Person].[Address].StateProvinceID
Object
[AdventureWorks2016].[Person].[Address].
[PK_Address_AddressID]
Output List
[AdventureWorks2016].[Person].[Address].City

Non-Clustered Index with Included Column



Included columns for non-clustered indexes

Included as additional non-key columns of data in the leaf level.

Allows for covering more queries.

As query optimizer can locate column values in index (leaf level) hence performance gain is achieved.

Not restricted to a Maximum of 32 key columns and index key size of 1,700 bytes.

(n)varchar(max) can be used, but not (n)text or image data types.

Index search is not permitted on non-key columns.

Demonstration

Access Methods

Demonstrate seeks, scans, and lookups

Questions?

Knowledge Check

What are the three access methods reviewed in this lesson?

What are the three different types of allocations?

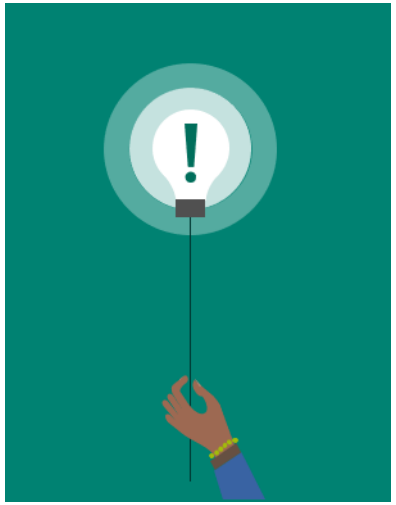
What is the primary goal of indexing?

Lesson 2: Index Strategy

Objectives

After completing this learning, you will be able to:

- Describe best practices associated with clustered index design.
- Consider factors involved in designing a nonclustered indexing strategy.
- Explain how an indexing strategy can reduce logical reads.
- Describe use of Filter indexes and Indexed views.
- Explain the role of Fill factor.
- Use a technique to reduce the fragmentation.
- Apply Index Compression.



Characteristics of a Good Clustering Key

Narrow	Unique	Static	Increasing
• Use a data type with a small number of bytes to conserve space in tables and indexes	• To avoid SQL adding a 4-byte uniquifier	• Allows data to stay constant without constant changes which could lead to page splits	• Allows better write performance and reduces fragmentation issues

Best Practices for Clustered indexes

The primary goal of any indexing strategy is to make queries faster

Best Practice	Seeks, not scans	Avoid key lookups	Get most rows on the index page	Get most rows on the data page	Avoid page splits
Use frequently searched value	X	X			
Use narrow keys			X	X	
Use unique values			X	X	
Use static values					X
Use ascending or descending key					X

Clustered Index vs Primary key considerations

Frequently, clustering on the primary key supports the clustered index best practices

- Query predicate use Primary Key
- Primary keys are involved in joins to foreign keys
- Primary keys are unique
- Primary keys are typically ascending
- Primary keys are typically not updated

Do not cluster on the Primary key IF:

- When table is accessed by other keys than the primary key
- Common issue accessing association or child table, when these tables require different primary key than parent table
- Use sys.dm_db_index_usage_stats to review data access patterns of index

Non-Clustered Index Strategy

Index columns used in WHERE clauses and JOINs.

Keep indexes to a minimum, to minimize impact on DML and log writes.

Two basic approaches: Single column indexes or Multicolumn indexes

Easy to create too many nonclustered indexes.

Specific indexes are appropriate for high-impact queries.

Ideally the focus should be writing queries to use existing indexes, rather than on adding more indexes.

Single Vs Multi-column indexes

Single-column Indexing

- Good choice for columns that are highly selective, or columns referenced often by criteria.
- When filtering data from table with multiple single column indexes, SQL uses the index with higher cardinality column, it may be better to not index the low cardinality column.

Multi-Column Indexing

- Good choice for low cardinality columns.
- Highest cardinality field first, to zoom into a narrow range of the B-Tree as quickly as possible.
- Equality columns before inequality columns.

Multi-Column Indexing Access

Seek only happens if you search for the columns in the specified order.

CREATE INDEX IX1 ON TABLE (PostalCode, StateID, City)

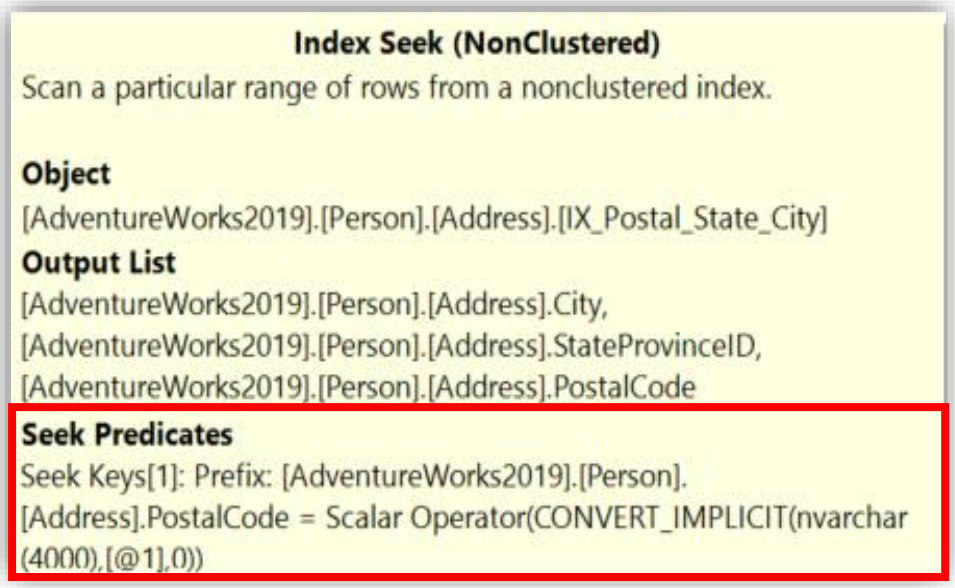
Effect of column in different WHERE clause.

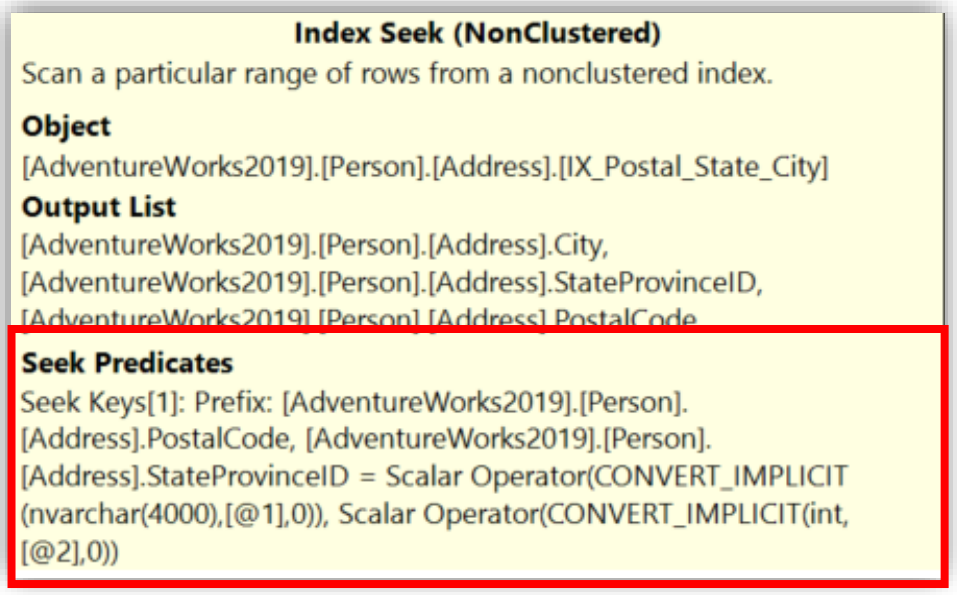
- WHERE PostalCode = 98011 – seek
- WHERE PostalCode = 98011 AND StateID = 79 – seek both
- WHERE PostalCode = 98011 – seek AND City = Bothell -- scan
- WHERE StateID = 79 -- scan

Multi-Column Indexing Access (Seek Predicates)

```
--Single value performs Index Seek.
SELECT City, StateProvinceID,
PostalCode
FROM Person.Address
WHERE PostalCode = '98011'
```

```
--Index Seek on both columns
--Search condition in same order as Index.
SELECT City, StateProvinceID, PostalCode
FROM Person.Address
WHERE PostalCode = '98011' AND
StateProvinceID = 79
```





Multi-Column Indexing Access (Scan Predicates)

```
--Index Seek on first column
--After seek, will scan second column
SELECT City, StateProvinceID, PostalCode
FROM Person.Address
WHERE PostalCode = '98011' AND City =
'Bothell'
```

```
--Search condition not in same order as
Index.
--Performs Index Scan.
SELECT  City, StateProvinceID, PostalCode
FROM Person.Address
WHERE StateProvinceID = 79
```

Index Seek (NonClustered)

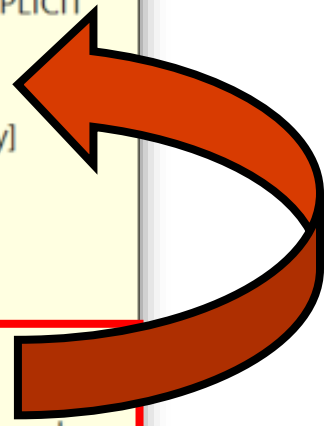
Scan a particular range of rows from a nonclustered index.

Predicate
[AdventureWorks2019].[Person].[Address].[City]=CONVERT_IMPLICIT
(nvarchar(4000),[@2],0)

Object
[AdventureWorks2019].[Person].[Address].[IX_Postal_State_City]

Output List
[AdventureWorks2019].[Person].[Address].City,
[AdventureWorks2019].[Person].[Address].StateProvinceID,
[AdventureWorks2019].[Person].[Address].PostalCode

Seek Predicates
Seek Keys[1]: Prefix: [AdventureWorks2019].[Person].
[Address].PostalCode = Scalar Operator(CONVERT_IMPLICIT(nvarchar
(4000),[@1],0))



Index Scan (NonClustered)

Scan a nonclustered index, entirely or only a range.

Predicate
[AdventureWorks2019].[Person].[Address].[StateProvinceID]=(79)

Object
[AdventureWorks2019].[Person].[Address].[IX_Postal_State_City]

Output List
[AdventureWorks2019].[Person].[Address].City,
[AdventureWorks2019].[Person].[Address].StateProvinceID,
[AdventureWorks2019].[Person].[Address].PostalCode

Demonstration

Analyzing Index Usage

Show how index usage patterns can help identify index and query improvements.

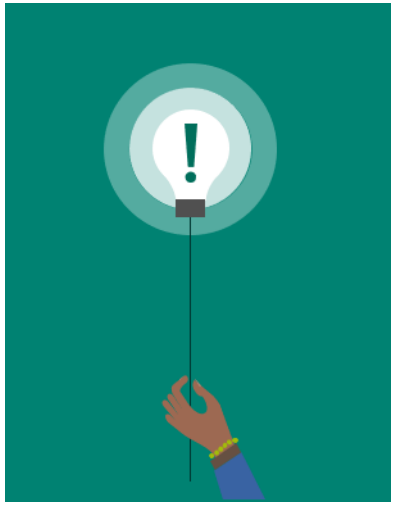
Questions?

Lesson 3: Partitioned Tables and Indexes

Objectives

After completing this learning, you will be able to:

- Understand Partition Concepts.
- Explain benefits of partitioning.
- Distinguish between aligned vs non-aligned indexes.
- Manage partitions.
- Apply Partition performance guidelines.



What is Partitioning?

"Horizontal Partition"

Table or Index Partition

- Breaking a single table or index into multiple HoBT (Heap or B-Tree) structures
- Requires a single column to use as partition key
- Partitioning is transparent to all queries

Partitioning benefits

Data Access

- Faster data load and offload.
- Query performance may be improved:
  - when predicate uses Partition-Key → partition elimination
  - when predicate doesn't use partition key → parallel execution

Maintenance and management

- Data placement handled by SQL Server.
- Piecemeal backup / restore of data by partition.
- Per-Partition management available for:
  - Index Maintenance
  - Lock Escalation
  - Compression

Horizontal Partitioning

Table without Partition

ProductKey	OrderDateKey	CustomerKey	SalesOrderNumber	UnitPrice	ExtendedAmount	ProductStandardCost
312	20050922	28191	SO44236	3578.27	3578.27	2171.2942
313	20050923	28163	SO44242	3578.27	3578.27	2171.2942
314	20050926	28142	SO44254	3578.27	3578.27	2171.2942
312	20050927	28171	SO44259	3578.27	3578.27	2171.2942

Table with Partition

Partition Key

Partition 1

ProductKey	OrderDateKey	CustomerKey	SalesOrderNumber	UnitPrice	ExtendedAmount	ProductStandardCost
312	20050922	28191	SO44236	3578.27	3578.27	2171.2942
313	20050923	28163	SO44242	3578.27	3578.27	2171.2942

Partition 2

ProductKey	OrderDateKey	CustomerKey	SalesOrderNumber	UnitPrice	ExtendedAmount	ProductStandardCost
314	20050926	28142	SO44254	3578.27	3578.27	2171.2942
312	20050927	28171	SO44259	3578.27	3578.27	2171.2942

Table Partitioning Concepts

Partition Function

- Defines how the table is logically partitioned.
- Defines data type of partition key, and ranges of each partition.
- Ranges can be modified as needed.

Partition Schemes

- Specify mapping from partitioned table to Filegroup(s).
- Uses *Partition Function* to perform mapping.
- Different filegroups can provide increased performance, but is not required.

Partition Column (key)

- Column used to apply partition function.
- If using a computed column, it must be explicitly marked as PERSISTED.

Partition Table & index

- Partitioned Tables are defined using *Partition Schemes*.
- Several tables may share common Partition Functions and Partition Schemes.
- Loading data into the table or index creation, will move data to correct partition automatically.

Aligned vs Non-aligned indexes

Aligned Index

- An index that is built on the same partition scheme as its corresponding table.
- When a table and its indexes Align, SQL Server can switch partitions quickly and efficiently.

Non-aligned index

- An index partitioned independently from its corresponding table.
- Designing a non-aligned partitioned index can be useful in the following cases:
  - The base table has not been partitioned.
  - The index key is unique, and it does not contain the partitioning column of the table.
  - Useful when want to joins with more tables using different join columns.

Indexes on Partitioned Table

Logical Alignment

- Indexes are logically aligned when they use partitioning column.

Storage Alignment

- Indexes are storage aligned when created on the same partitioning scheme.
- By default, indexes will be created ON the partition scheme – ‘storage aligned’ indexes.

```
CREATE [CLUSTERED] INDEX … ON {partition_scheme_name ( column_name ) }
```

Partitioned table and index sample

```
-- Creating a partition function with four partitions
CREATE PARTITION FUNCTION myRangePF1 (int)
    AS RANGE LEFT FOR VALUES (1, 100, 1000) ;
GO
-- Creates a partition scheme that applies myRangePF1 to the four filegroups
CREATE PARTITION SCHEME myRangePS1
    AS PARTITION myRangePF1
    TO (test1fg, test2fg, test3fg, test4fg) ;
GO
-- Creates a partitioned table that uses myRangePS1 to partition col1
CREATE TABLE PartitionTable (col1 int NOT NULL, col2 char(10))
    ON myRangePS1 (col1) ;
GO
CREATE CLUSTERED INDEX ClusIndxCol1 ON PartitionTable(col1)
ON myRangePS1(col1)
GO
```

Table Partitioning Operations

Data Movement in table or Partition is done using ALTER …SWITCH/MERGE/SPLIT

SWITCH	MERGE	SPLIT
• Uses staging table • MUST have same schema as Partitioned table	• Used to eliminate an empty partition, by merging it with another partition	• Used to create a new empty partition from an existing partition

```
--SWITCH
ALTER TABLE PartitionTable SWITCH PARTITION 2 TO NonPartitionTable ;
--SPLIT
CREATE PARTITION FUNCTION myRangePF1 (int) AS RANGE LEFT FOR VALUES ( 1, 100, 1000 );
ALTER PARTITION FUNCTION myRangePF1() SPLIT RANGE (500);
--MERGE
CREATE PARTITION FUNCTION myRangePF1 (int) AS RANGE LEFT FOR VALUES ( 1, 100, 1000 );
ALTER PARTITION FUNCTION myRangePF1() MERGE RANGE (100);
```

Demonstration

Partitioning

Explore Partition Schemes and Functions.

SQL Server Partitioning

- Practicing with a sliding partition window

Questions?

Knowledge Check

What three structures are required to support partitions?

What are some benefits of partitioning?

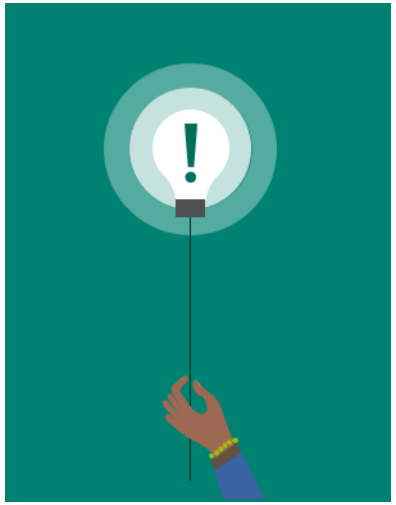
What is used for data movement in partitions or table?

Lesson 4: Index Monitoring and Fragmentation

Objectives

After completing this learning, you will be able to:

- Monitor index usage.
- Describe page splits.
- Understand problems caused by page splits.
- Monitor index fragmentation and free space.
- Review options to remove fragmentation and free space.



Why to monitor Index usage

Data access and distribution changes over time.

By reviewing index usage, we can ensure that the indexes are appropriate for the current workload.

Use sys.dm_db_index_usage_stats and sys.dm_db_index_operational_stats to monitor index usage.

Database standard report also monitors Index usage and Physical Statistics.

Clustered Index usage patterns

Pattern	Interpretation
Seeks, but no scans	• May not need maintenance. Seeks are not impacted by fragmentation
Clustered index with High number of scans	• Review missing index recommendations. • Consider changing Clustering key. • Simplify queries with complex WHERE clauses
Clustered index with Low number of seeks and high number of lookups	• May need to change Clustering Key • Look how often bookmark lookups occur.

Non-Clustered Index usage patterns

Pattern	Interpretation
Seeks, but no scans	• May not need maintenance. • Seeks are not impacted by fragmentation
Non-Clustered index with High number of scans	• Consider compression. • Check for non-SARGable queries. • Review missing index recommendations
Index with No/low usage	• May be able to drop or disable index
Non-Clustered Index Used at specific times only	• May be able to drop index, recreate when needed

sys.dm_db_index_usage_stats

- Tracks seeks, scans, and lookups
- Provides date of last access
- Counters are incremented once per query execution
- User and system access (such as index rebuilds) are tallied separately
- Counters are initialized to at SQL Server (MSSQLSERVER) service is restarts

```
SELECT
        Distinct OBJECT_NAME(Indx.OBJECT_ID) Table_Name  ,Indx.name  IndexName
        ,Indx.type_desc IndexType,Iusg.user_seeks  Seeks,Iusg.user_scans  Scans
        ,Iusg.user_lookups  Lookups ,Iusg.user_updates Updates ,Iusg.last_user_seek LastSeek
        ,Iusg.last_user_scan LastScan,Iusg.last_user_lookup LastLookup ,Iusg.last_user_update LastUpdate
FROM
        SYS.INDEXES Indx
        INNER JOIN SYS.DM_DB_INDEX_USAGE_STATS Iusg
                ON Iusg.index_id = Indx.index_id AND Iusg.OBJECT_ID = Indx.OBJECT_ID
        INNER JOIN SYS.DM_DB_PARTITION_STATS PrtSts
                ON PrtSts.object_id=Indx.object_id
WHERE
        OBJECTPROPERTY(Indx.OBJECT_ID,'IsUserTable') = 1
```

sys.dm_db_index_operational_stats

- Returns information about the lower-level I/O activities
- Takes database_id, the object_id, the index_id and the partition_number as parameters
- Memory-optimized indexes do not appear in this DMV

```
SELECT
        *
FROM
        SYS.DM_DB_INDEX_OPERATIONAL_STATS (NULL,NULL,NULL,NULL ) opsts
        INNER JOIN SYS.INDEXES AS Indx
                ON Indx.[OBJECT_ID] = opsts.[OBJECT_ID]
                AND Indx.INDEX_ID = opsts.INDEX_ID
WHERE
        OBJECTPROPERTY(opsts.[OBJECT_ID],'IsUserTable') = 1
```

sys.dm_db_index_physical_stats

- Returns size and fragmentation information for the data and indexes of the specified table or view in SQL Server.
- Takes database_id, the object_id, the index_id and the partition_number as parameters
- Memory-optimized indexes do not appear in this DMV

```
SELECT OBJECT_SCHEMA_NAME(I.object_id) AS SchemaName, OBJECT_NAME(I.object_id) AS
TableName, I.name, I.Index_ID, IPS.partition_number, IPS.avg_fragmentation_in_percent,
   IPS.page_count, IPS.avg_page_space_used_in_percent
FROM sys.indexes as I
INNER JOIN sys.dm_db_index_physical_stats(DB_ID(), NULL, NULL, NULL, 'Limited') as IPS
ON I.object_id = IPS. object_id
AND I.index_id = IPS.index_id
--WHERE IPS.avg_fragmentation_in_percent >30
--AND IPS.page_count >1000
```

Fragmentation

A fragmented table/Index is when some of its data pages point to pages that are not in sequence.

Logical fragmentation

- Occurs when leaf level pages are not physically corresponding to the logical order of the index:
  - Pages are not in the most efficient order for scanning purposes.
- Limits the efficiency of read-ahead scans, but not seeks.

Page density

- How full a page is when a rebuild/reorganization occurs.
- The fuller a page is, the more likely page splits occur when data is modified.
- The less full a page is, the more wasted space in the buffer pool when reading pages.

Page splits

Mechanism to optimize inserts and updates

Occurs when page is full to hold a new or updated row

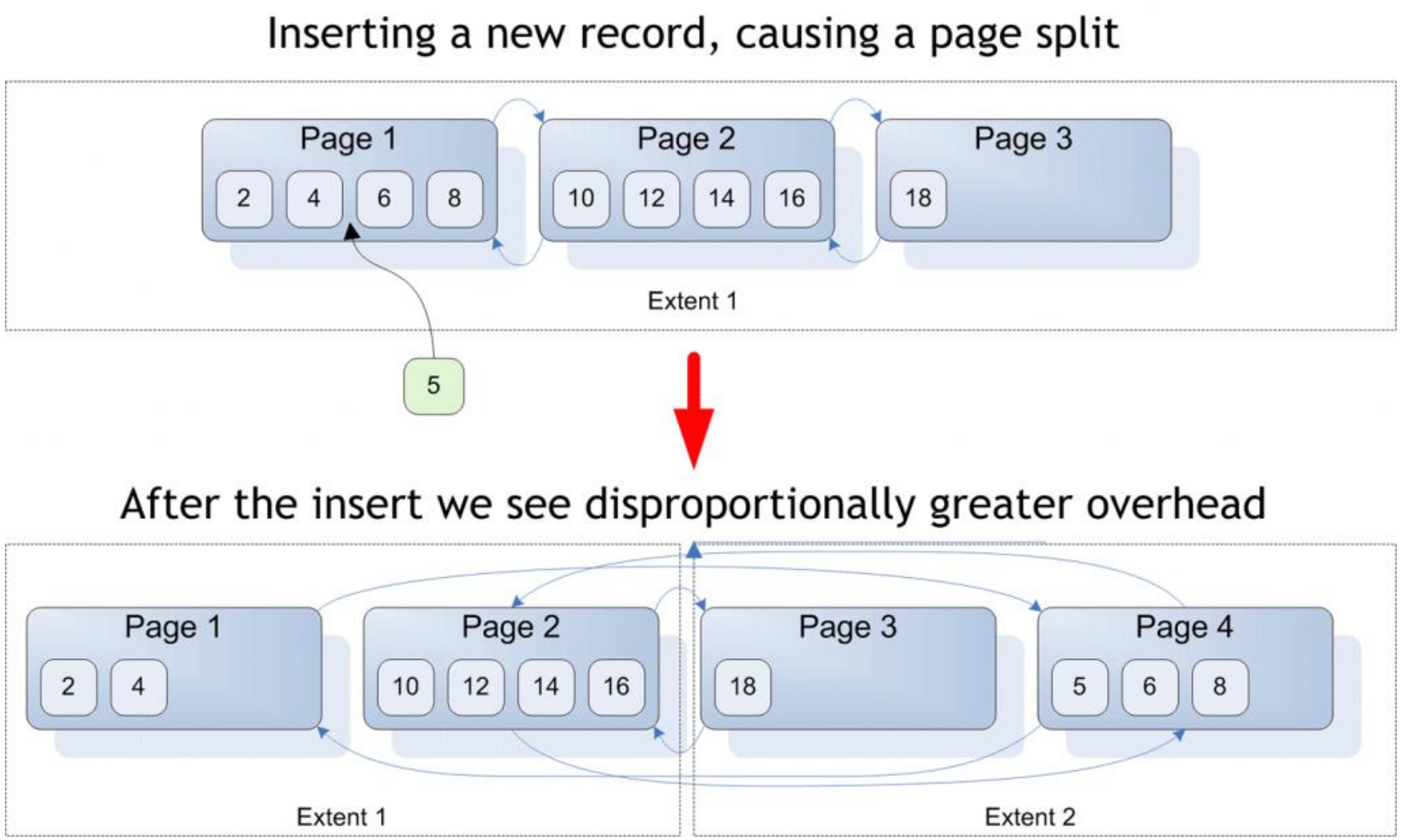
Half the rows are moved to a new page

The new page is added after the last existing page

Cost associated with Page splits

- Fragmentation, which affects scan performance
- Wasted free space, which affects Page Density

Page Splits


Inserting a new record, causing a page split
Page 1
2
4
6
8
Page 2
10
12
14
16
Page 3
18
Extent 1
5
After the insert we see disproportionally greater overhead
Page 1
2
4
Page 2
10
12
14
16
Page 3
18
Page 4
5
6
8
Extent 1
Extent 2

SQL Index Fragmentation and Maintenance options

SSMS -> Index Physical Statistics report

- Will report fragmentation and recommend solution at database level

Custom Solution

- Find fragmentation using Sys.dm_db_index_physical_stats
- Correct fragmentation

Can remove Index fragmentation using Rebuild or Reorganize option

	ALTER INDEX... REBUILD	ALTER INDEX ... REORGANIZE
Removes fragmentation	X	X
Removes free space	X	
Resets fill factor	X	
Updates statistics	X	

Fill Factor

Can address performance issues due to fragmentation.

Use When

- Specifying the amount of free space on a data or index page.
- Reducing logical fragmentation.

Do not use when

- Low fragmentation
- High seeks and low scans
- Index is not scanned

```
ALTER INDEX [pk_bigProduct]
ON [dbo].[bigProduct]
REBUILD WITH (PAD_INDEX = ON, FILLFACTOR = 90)
```

Reducing fragmentation

Reducing Fragmentation

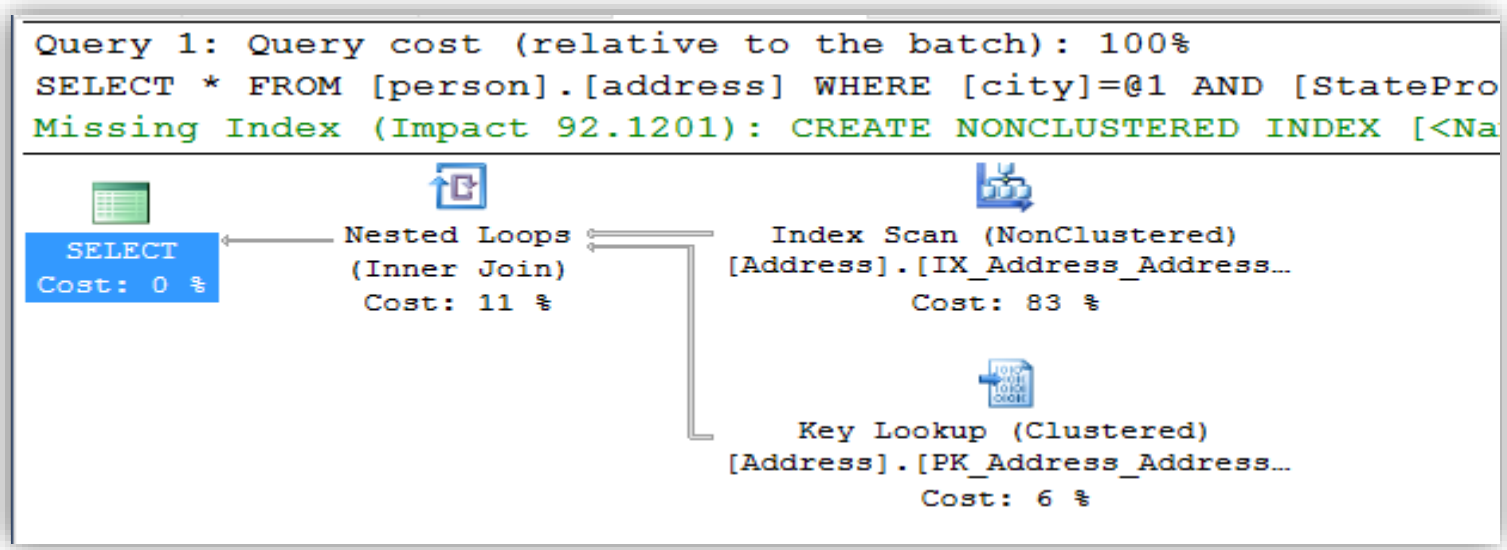
- Using an ascending key (not always possible).
- Using an appropriate fill factor for the workload.
- Update in sets, rather than one at a time.
- Do not insert with immediate update.

Missing Index Recommendations

SQL Server identifies indexes that would help a query's performance

The recommendation is included in the query plan

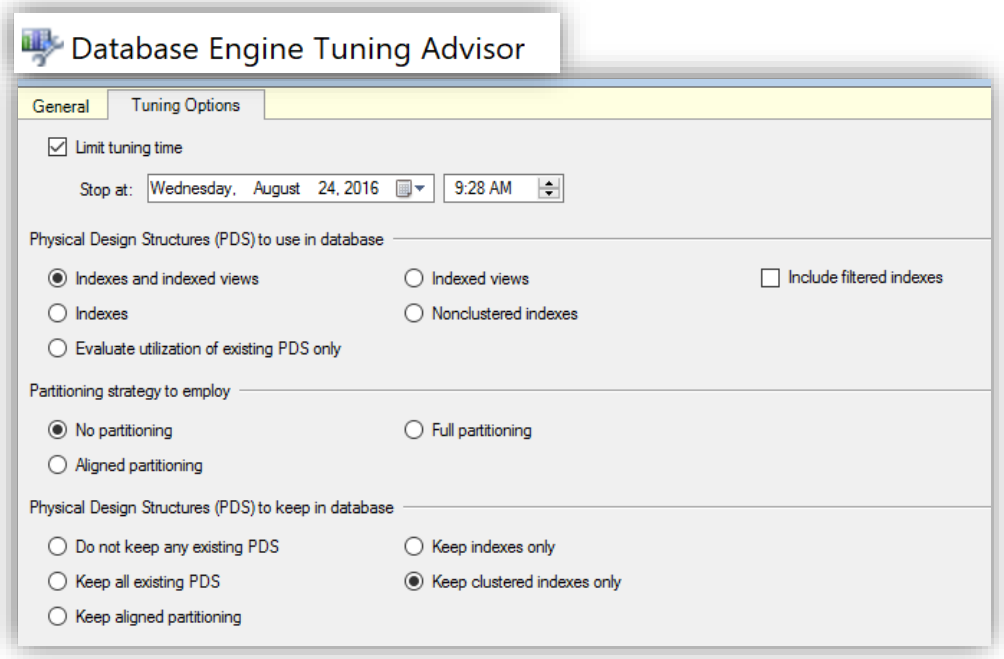
The cost savings are aggregated in DMVs to help identify the most beneficial indexes



Choosing Indexes

Following sources can help you choosing indexes

- Missing Index recommendations
- sys.dm_db_index_usage_stats
- Database Tuning Advisor



Demonstration

Analyzing Index Usage

Show how index usage patterns can help identify index and query improvements.

Index Maintenance

- Identifying and removing physical index fragmentation

Questions?

Knowledge Check

Which DMV/DMF are used to monitor index usage?

Does it make sense to add all SQL Server missing recommendations?

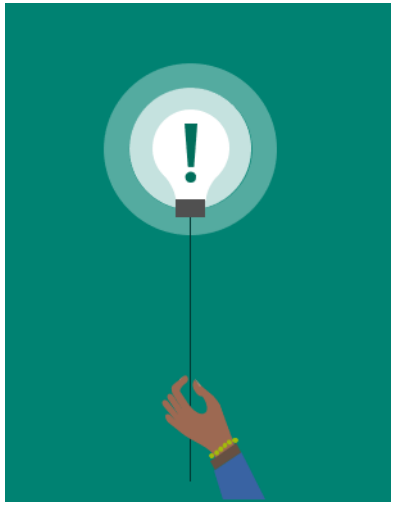
When Managed Lock Priority should be used?

Lesson 5: Columnstore Indexes

Objectives

After completing this learning, you will be able to:

- Understand the differences between rowstore and Columnstore indexes.
- Understand the primary use case for Columnstore indexes.
- Examine and monitor Columnstore indexes.

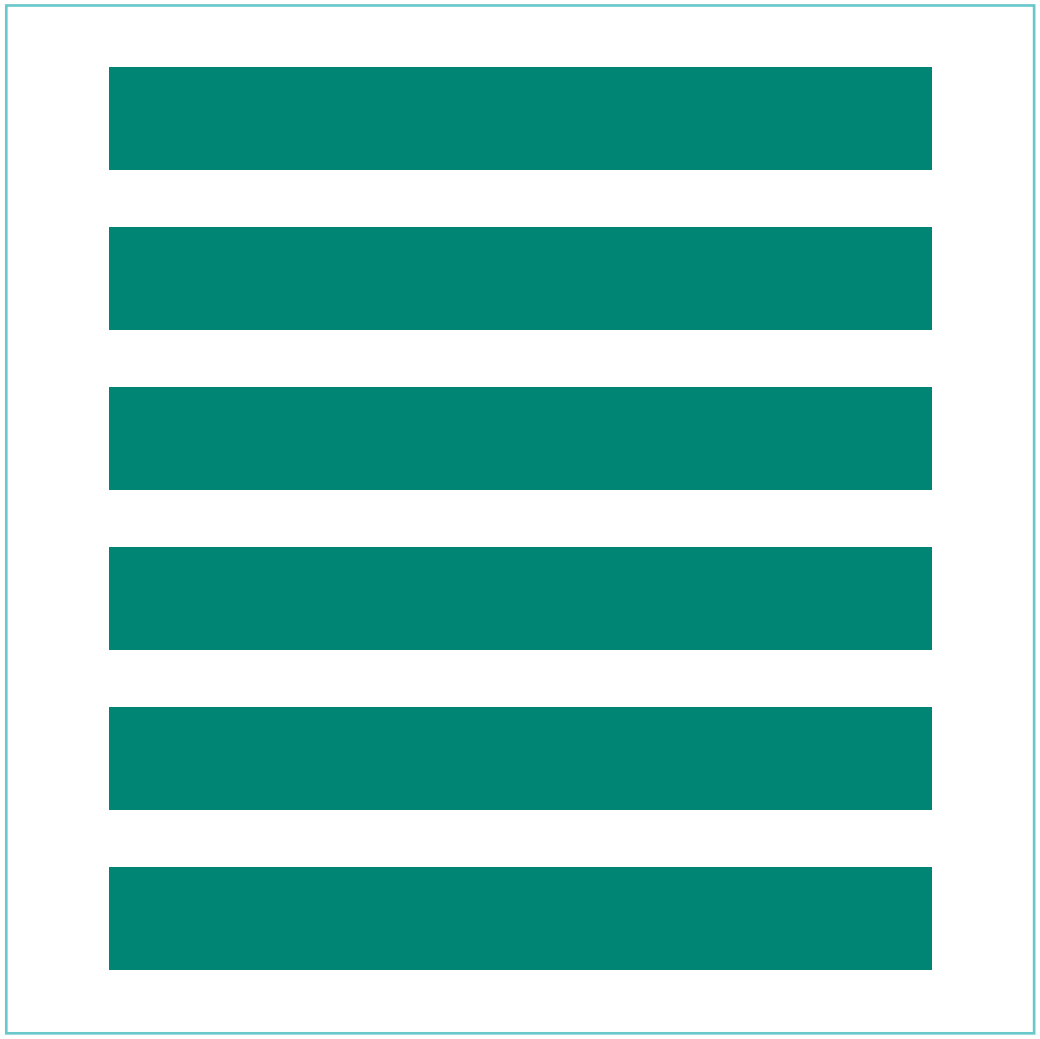


Rowstore INDEX design

- Up to 1,000 indexes per table
- Up to 16 columns for index key
- 900 bytes per clustered index
- 1700 bytes per non-clustered index

Regular types of indexes (Clustered / Non-Clustered) wouldn't be able to handle the workload.
It will be impractical to create indexes on all individual columns, or to create all possible column combinations.

RowStore vs ColumnStore



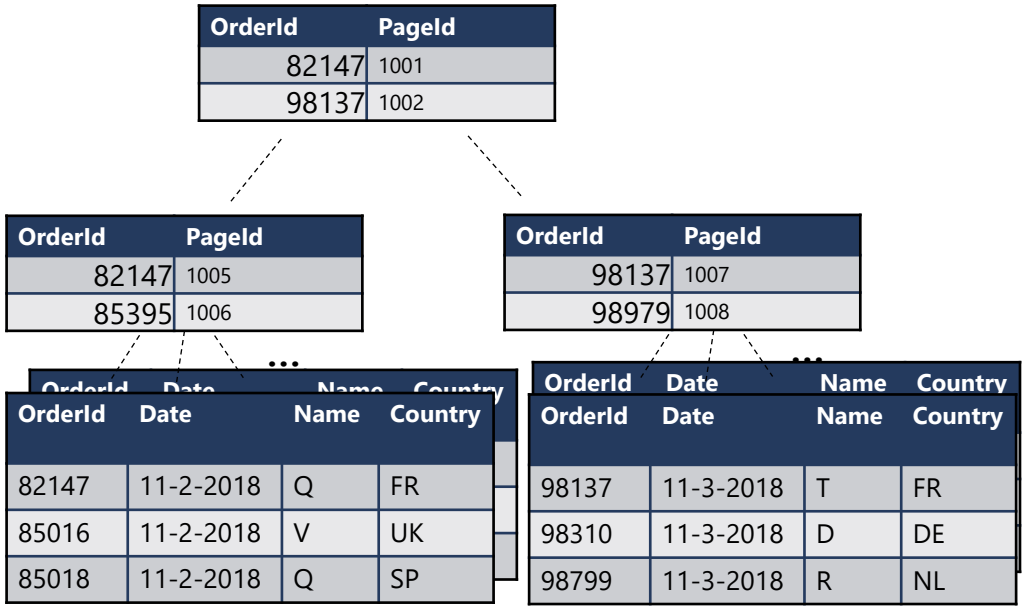
Rowstore vs Columnstore Tables

Logical table structure

OrderId	Date	Name	Country
85016	11-2-2018	V	UK
85018	11-2-2018	Q	SP
85216	11-2-2018	Q	DE
85395	11-2-2018	V	NL
82147	11-2-2018	Q	FR
86881	11-2-2018	D	UK
93080	11-3-2018	R	UK
94156	11-3-2018	S	FR
96250	11-3-2018	Q	NL
98799	11-3-2018	R	NL
98015	11-3-2018	T	UK
98310	11-3-2018	D	DE
98979	11-3-2018	Z	DE
98137	11-3-2018	T	FR
...	...	...	...

Clustered/Non-clustered rowstore index

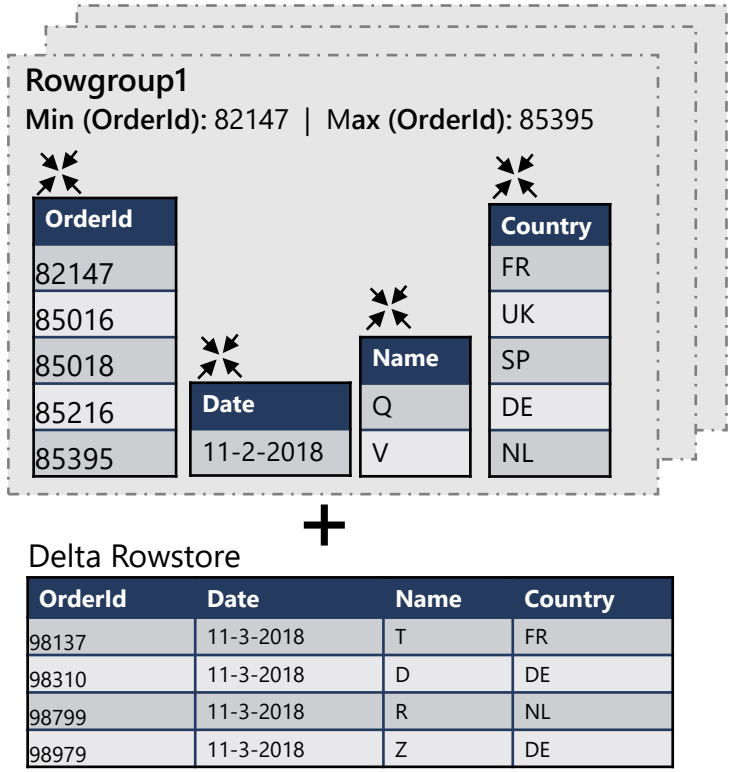
(OrderId)



- Data is stored in a B-tree index structure for performant lookup queries for particular rows.
- Clustered rowstore index: The leaf nodes in the structure store the data values in a row (as pictured above)
- Non-clustered (secondary) rowstore index: The leaf nodes store pointers to the data values, not the values themselves

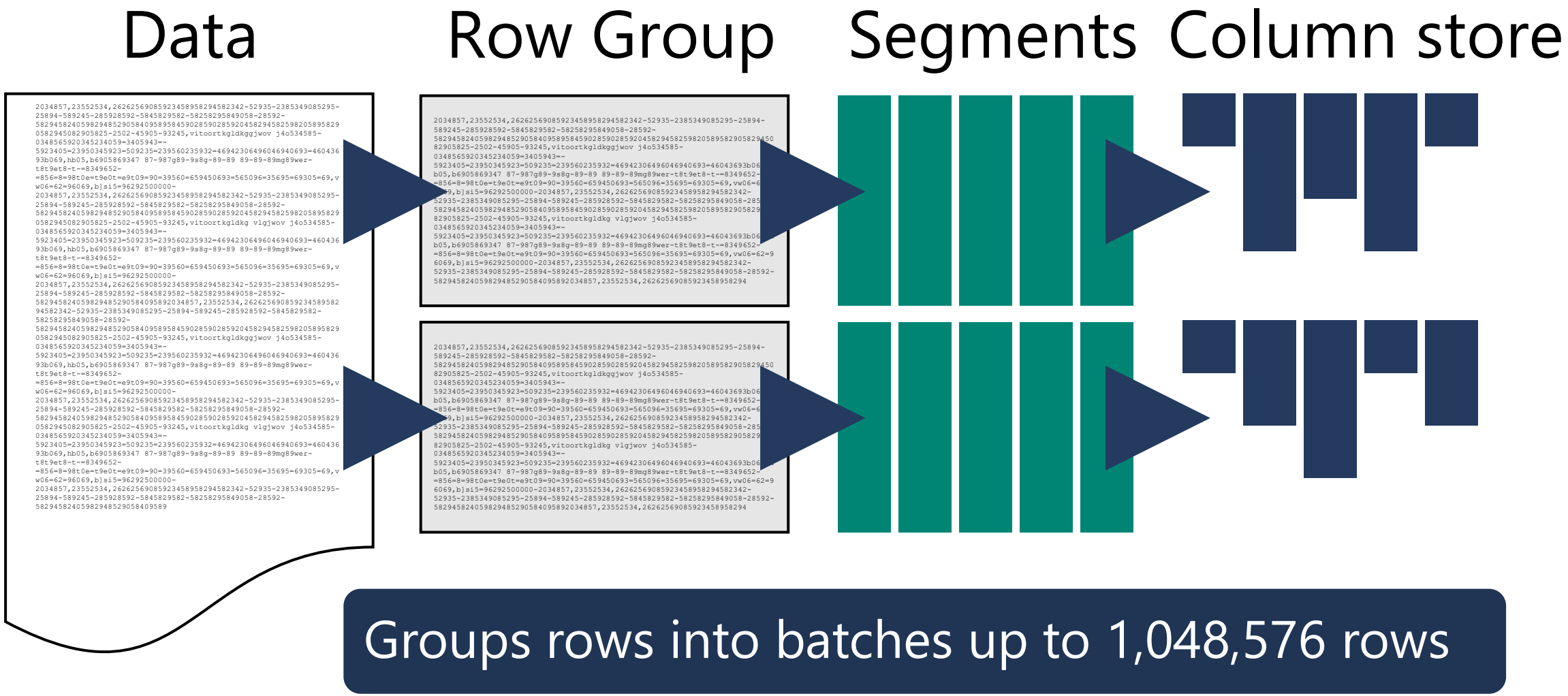
Clustered columnstore index

(OrderId)



- Data stored in compressed columnstore segments after being sliced into groups of rows (rowgroups/micro-partitions) for maximum compression
- Rows are stored in the delta rowstore until the number of rows is large enough to be compressed into a columnstore

Columnstore Index Concept



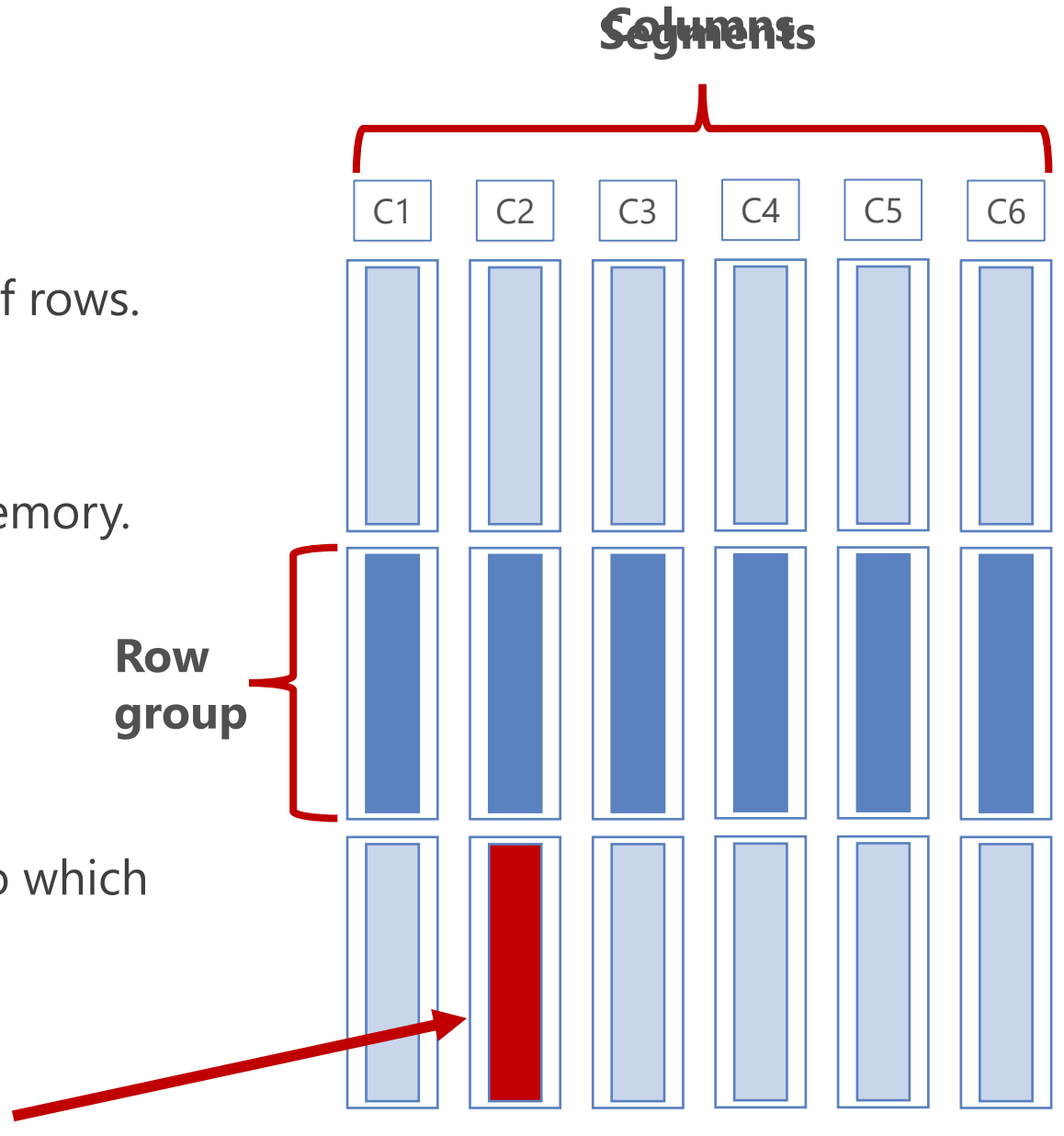
Row Groups & Segments

Segment

- Contains values for one column for a set of rows.
- Segments are compressed.
- Each segment is stored in a separate LOB.
- It is a unit of transfer between disk and memory.

Row Group

- Segments for the same set of rows comprise a row group.
- Position of a value in a column indicates to which row it belongs to.



Columnstore Index Types

Clustered Index

- Use to store fact tables and large dimension tables for data warehousing workloads
- IOT workloads that insert large volumes with minimal updates/deletes
- Average of 10x Compressions
- Covers Entire Table
- May have one or more Nonclustered B-Tree Indexes

Non-Clustered Index

- Use to perform analysis in real time on an OLTP workload.
- Can be created for subset of columns

Columnstore Index Types

SQL Server 2012

- Only Non-Clustered, Non-Updatable Columnstore Indexes.
- Only available in Enterprise Edition.

SQL Server 2014

- Introduced Updatable, Clustered Columnstore Indexes
- Only available in Enterprise Edition.

SQL Server 2016

- Introduced Updatable, Non-Clustered Columnstore Indexes
- Available on Standard Edition. (Service Pack 1)

SQL Server 2019

- Online rebuilds for Clustered Columnstore Indexes.

Delta Store

Page compressed b-tree like a row store

- B-tree on unique integer row ID
- Matches user columns defined in the CCI
- Aligned to underlying CCI partition
- Small bulk loads of less than 102,400 rows, go directly to the deltastore.

Max # rows
delta store
1,048,576

Small DML Against the Column Store

Inserts

- Below threshold? Write to the delta store
- Above threshold? Write as column store

Deletes

- Logical against rows in column store
- Physically against rows in the delta store

Updates

- Converted to a logical delete and an insert

Segment Elimination

Skips large chunks of data to speed up scans

Each partition in a column store index is broken into segments

Each segment has metadata that stores the minimum and maximum value of each column for the segment

The storage engine checks filter conditions against the metadata

If it detects no rows that qualify, it skips the entire segment without reading it from disk

Segment / RowGroup Elimination

```
SELECT ProductKey,  SUM(SalesAmount)
FROM SalesTable
WHERE OrderDateKey < '20101108'
```

Rowgroup # 1

RegionKey	Quantity	StoreKey	ProductKey	OrderDateKey	SalesAmount
1	6	01	106	20101107	30.00
2	1	04	103	20101107	17.00
2	2	04	109	20101107	20.00
2	1	03	103	20101107	17.00
3	4	05	106	20101107	20.00
1	5	02	106	20101108	25.00

Rowgroup # 2

RegionKey	Quantity	StoreKey	ProductKey	OrderDateKey	SalesAmount
1	1	02	102	20101108	14.00
2	5	03	106	20101108	25.00
1	1	01	109	20101108	10.00
2	4	04	106	20101109	20.00
2	5	04	106	20101109	25.00
1	1	01	103	20101109	17.00

Segment / RowGroup Elimination

Segment Elimination

```
SELECT ProductKey,  SUM(SalesAmount)
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RegionKey	Quantity	StoreKey	ProductKey	OrderDateKey	SalesAmount
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2	1	04	103	20101107	17.00
2	2	04	109	20101107	20.00
2	1	03	103	20101107	17.00
3	4	05	106	20101107	20.00
1	3	02	106	20101108	25.00

Rowgroup # 2

RegionKey	Quantity	StoreKey	ProductKey	OrderDateKey	SalesAmount
1	1	02	102	20101108	14.00
2	5	03	106	20101108	25.00
1	1	01	109	20101108	10.00
2	4	04	106	20101109	20.00
2	5	04	106	20101109	25.00
1	1	01	103	20101109	17.00

Segment / RowGroup Elimination

Segment Elimination → RowGroup Elimination

```
SELECT ProductKey,  SUM(SalesAmount)
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```

Rowgroup # 1

RegionKey	Quantity	StoreKey	ProductKey	OrderDateKey	SalesAmount
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2	1	03	103	20101107	17.00
3	4	05	106	20101107	20.00
1	5	02	106	20101108	25.00

Rowgroup # 2

RegionKey	Quantity	StoreKey	ProductKey	OrderDateKey	SalesAmount
1	1	02	102	20101108	14.00
2	5	03	106	20101108	25.00
1	1	01	109	20101108	10.00
2	4	04	106	20101109	20.00
2	5	04	106	20101109	25.00
1	1	01	103	20101109	17.00

Segment / RowGroup Elimination

Results

```
SELECT ProductKey,  SUM(SalesAmount)
FROM SalesTable
WHERE OrderDateKey < '20101108'
```

Rowgroup # 1

RegionKey
1
2
2
2
3
1

Quantity
6
1
2
1
4
5

StoreKey
01
04
04
03
05
02

ProductKey	OrderDateKey	SalesAmount
106	20101107	30.00
103	20101107	17.00
109	20101107	20.00
103	20101107	17.00
106	20101107	20.00
106	20101108	25.00

Rowgroup # 2

RegionKey
1
2
1
2
2

Quantity
1
5
1
4
5
1

StoreKey
02
03
01
04
04
01

ProductKey
102
106
106
106
106
103

OrderDateKey
20101108
20101108
20101108
20101109
20101109

SalesAmount
14.00
25.00
10.00
20.00
17.00

Poor Workloads for CCI

Select * - lose the ability to do column elimination

Point-lookup – easier to find a particular row in a rowstore table

Selecting a range – rowstore can more easily grab that range of rows

A lot of DML – more overhead in CCI.

- UPDATE = DELETE old row, INSERT new row
- DELETE – rows are only logically deleted until an ALTER INDEX REBUILD* is issued

Batch Mode Processing

Process around 1000 rows at a time

As opposed to 1 row at a time with row-based processing

Not all query plan operators can perform batch processing

- nested loops
- merge join

Plan operators are expanded in SQL Server 2016+

Greatly reduced CPU time (7 to 40X)

ColumnStore Index Performance

- Measure the performance of rowstore indexes versus colunmstore indexes.

Questions?

Knowledge Check

Name a primary reason for implementing a column store index?

What is the purpose of segments?

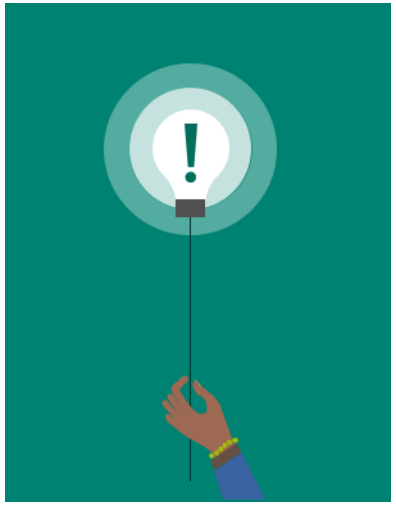
What is the purpose of row groups?

Extra: In-Memory OLTP

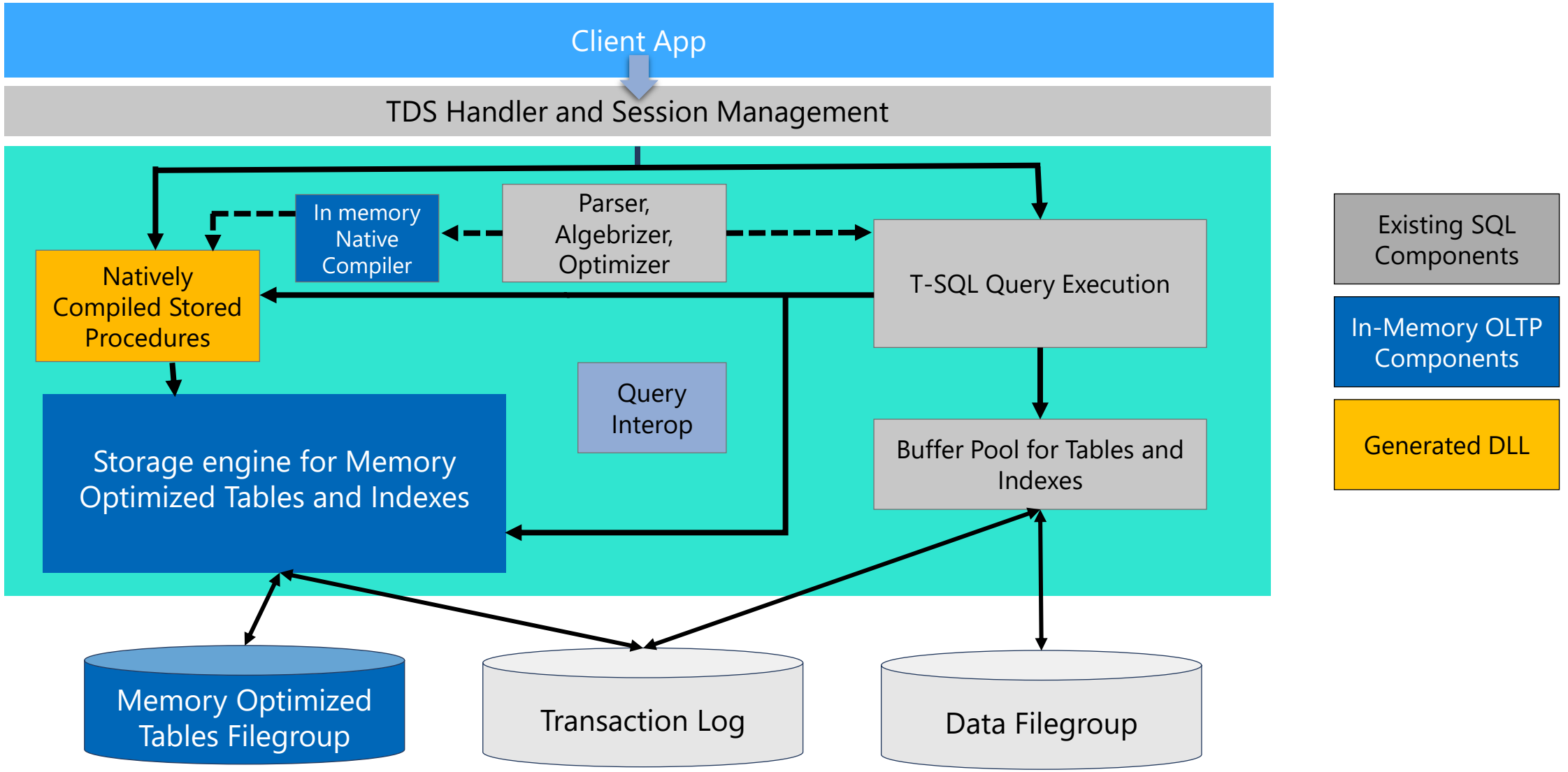
Objectives

After completing this learning, you will be able to:

- Understand the motivation behind Memory-Optimized objects.
- Describe the characteristics of Memory-Optimized objects.
- Monitor resources consumed by Memory-Optimized objects.



Memory Optimized Objects



Memory-Optimized objects

Recommended use

Use to get:

- Increased transaction throughput
- Improved data ingestion rate
- Reduced latency
- Transient data scenarios
- No locking
- No latching

Do not use when:

- Analytics/BI (consider Columnstore instead)
- Bottleneck is outside SQL:
  - Chatty App
  - Bottleneck is in the app
- Low transaction volume
- Resource limitations – not enough memory

Memory-Optimized Objects

Object types

Objects

- Tables
- Types

Code

- Natively compiled Stored Procedures
- Triggers
- Functions

Memory-Optimized Objects

Can be accessed via:

- Interop T-SQL allows for full range of SQL syntax
- Natively compiled Stored Procedures

Transactions involving Memory-Optimized tables are Atomic, Consistent, Isolated, and Durable (ACID)

Primary store for memory-optimized tables is main memory.

All operations on these objects happen in memory.

Durable

- Second copy of the table is maintained on disk

Non-Durable

- Not logged
- Data is not persisted on disk.

Memory-Optimized structure

Rows

- Row structure is optimized for memory access
- There is no concept of Pages
- Rows are Versioned and there are no in-place updates

Indexes

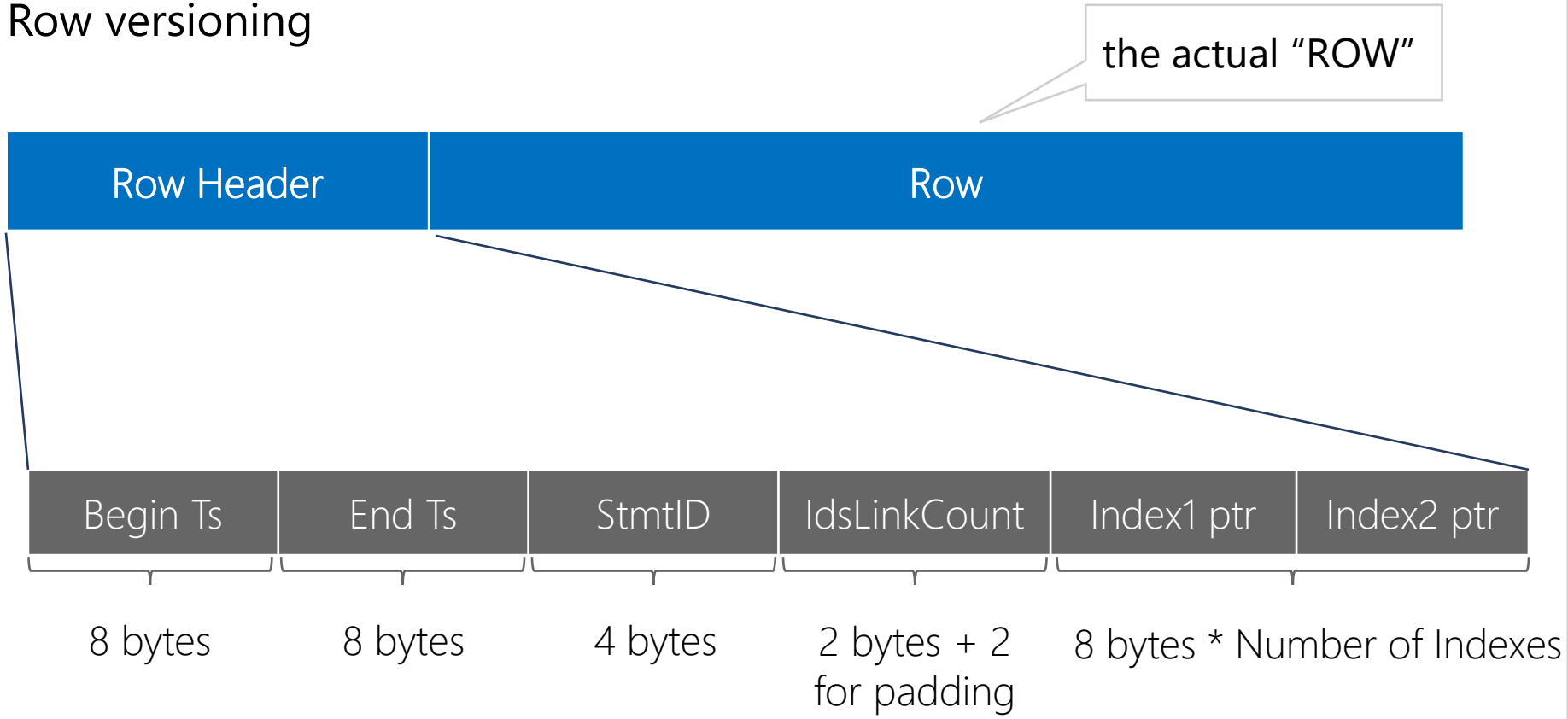
- Every memory-optimized object is required to have at least 1 index
- Indexes do not exist on disk.
  Only in memory.
  Recreated during recovery / restart

Index types:

- Hash indexes for point lookups
- Range indexes (non-clustered) for ordered scans and Range Scans
- There is no clustered Index
- Indexes point to rows, access to rows is via an index

Memory-Optimized Row Format

Row versioning



Begin/End timestamps determine row's version validity and visibility
TimeStamps are 64bit BIGINT

Internal counters used to manage timestamp values:

- **TRANSACTION-ID**: reset when instance is restarted. Incremented with every new transaction
- **GLOBAL**: not reset on SQL restart; Incremented each time a transaction ends
- **The oldest active running Transaction** in the system

Memory-Optimized

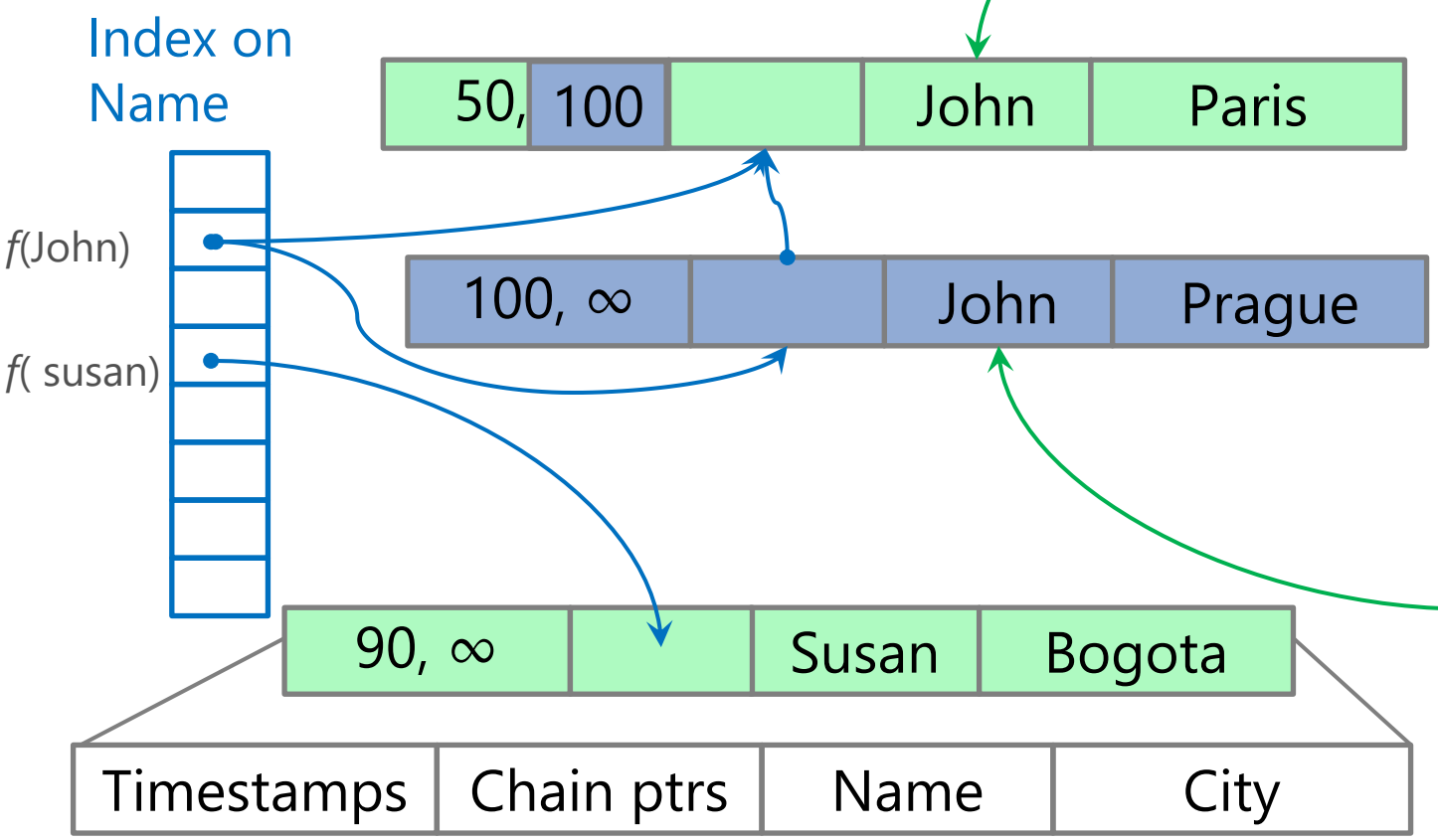
Row versions

- Rows are versioned
- Allows for concurrent reads and writes on the same row

Transaction 99: executes a SELECT

```
SELECT City
FROM <table>
WHERE Name = 'John'
```

Index seek returns pointer to row



Background operation will unlink and deallocate the old 'John' row after transaction 99 completes.

Transaction 100:

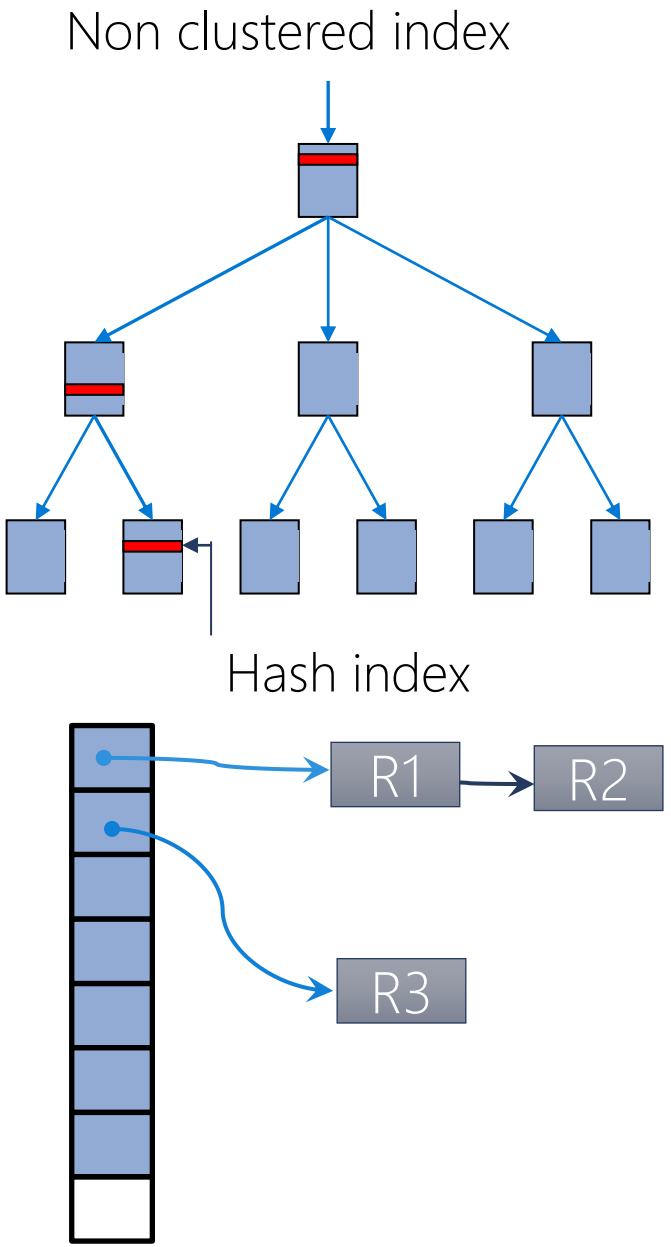
```
UPDATE  <table>
SET     City = 'Prague'
WHERE   Name = 'John'
```

no locks of any kind

no interference with transaction 99

Memory-Optimized Indexes

- Requirement: at least 1 index per table
- Memory structure that connects the rows
- Exists only in memory
  are not persisted to disk
- Loaded during table creation, or at server startup
- Inherently covering
- Fragmentation and fill-factor not applicable
- No logging for index operations



Memory-Optimized

Create Table DDL

```
CREATE TABLE [Customer](
    [CustomerID] INT NOT NULL
                PRIMARY KEY NONCLUSTERED HASH WITH (BUCKET_COUNT = 1000000),
    [Name] NVARCHAR(250) NOT NULL,
    [CustomerSince] DATETIME NULL
                INDEX [ICustomerSince] NONCLUSTERED
)
WITH (MEMORY_OPTIMIZED = ON, DURABILITY = SCHEMA_AND_DATA);
```

Hash Index
BUCKET_COUNT 1-2X nr of unique index key values actual count is the next integer power of 2

Indexes are specified inline

This table is memory optimized

This table is durable
Non-durable tables:
DURABILITY=SCHEMA_ONLY

Memory-Optimized

Create Stored Procedure DDL

```
CREATE PROCEDURE [dbo].[InsertOrder] @id INT, @date DATETIME
  WITH
   NATIVE_COMPILATION,
   SCHEMABINDING,
   EXECUTE AS OWNER
AS
BEGIN ATOMIC
  WITH
(TRANSACTION
   ISOLATION LEVEL = SNAPSHOT,
 LANGUAGE = N'us_english')

  -- insert T-SQL here
END
```

This proc is natively compiled

Native procs must be schema-bound

Execution context is required

Atomic blocks

- Create a transaction if there is none
- Otherwise, create a savepoint

Session settings are fixed at create time

Exploring In-memory OLTP Performance

- Comparing performance between Disk-Based and Memory-Optimized Tables