Column-Oriented Database Systems

VLDB 2009 Tutorial

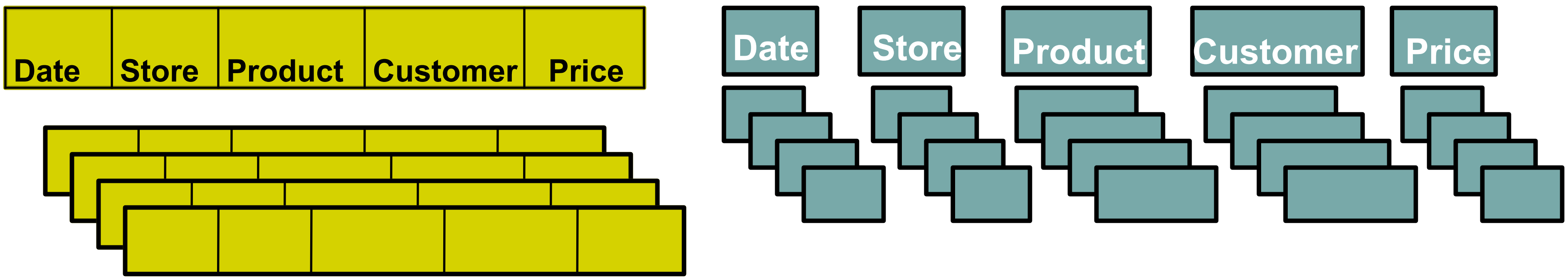
Part 1: Stavros Harizopoulos (HP Labs)

Part 2: Daniel Abadi (Yale)

Part 3: Peter Boncz (CWI)

What is a column-store?

row-store | **column-store**



+ easy to add/modify a record

- might read in unnecessary data

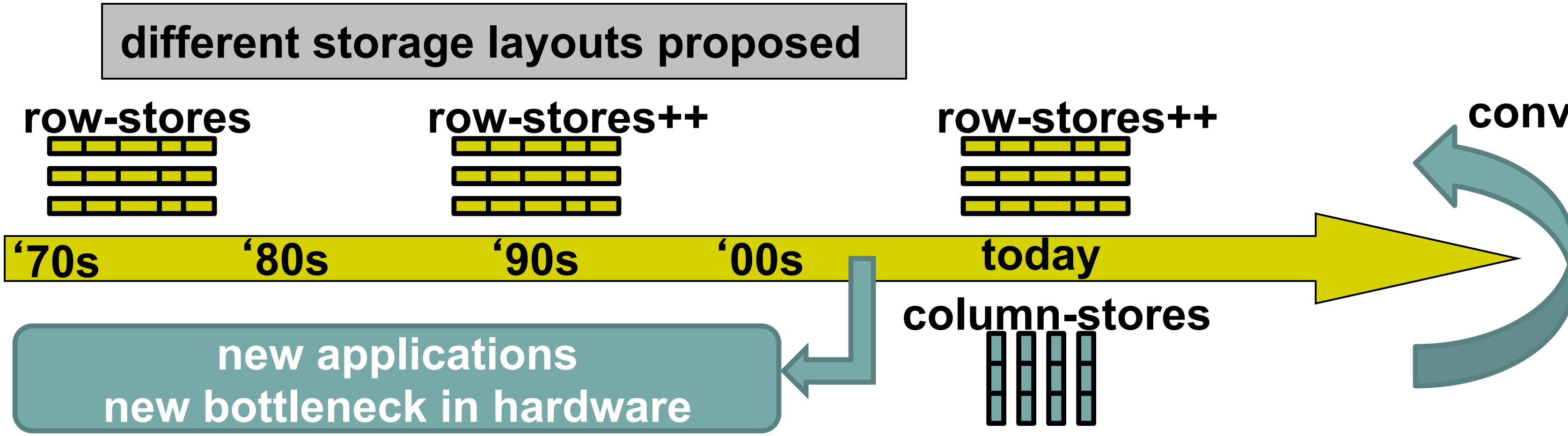
+ only need to read in relevant data

- tuple writes require multiple accesses

=> *suitable for read-mostly, read-intensive, large data repositories*

Are these two fundamentally different?

- The only fundamental difference is the storage layout
- However: we need to look at the big picture



- How did we get here, and where we are heading
- What are the column-specific optimizations?
- How do we improve CPU efficiency when operating on Cs

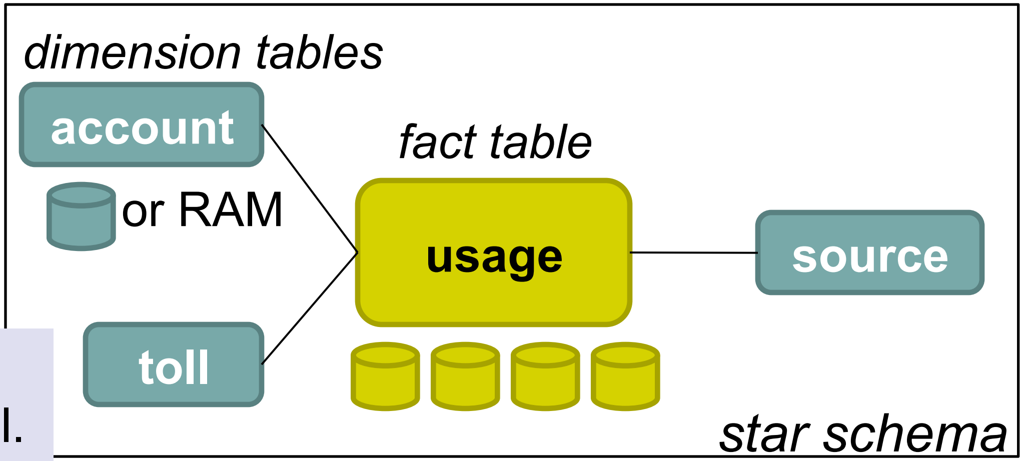
Part 1
Part 2
Part 3

Outline

- Part 1: Basic concepts — *Stavros*
  - Introduction to key features
  - From DSM to column-stores and performance tradeoffs
  - Column-store architecture overview
  - Will rows and columns ever converge?
- Part 2: Column-oriented execution — *Daniel*
- Part 3: MonetDB/X100 and CPU efficiency — *Peter*

Telco Data Warehousing example

- Typical DW installation
- Real-world example



"One Size Fits All? - Part 2: Benchmarking Results" Stonebraker et al. CIDR 2007

QUERY 2

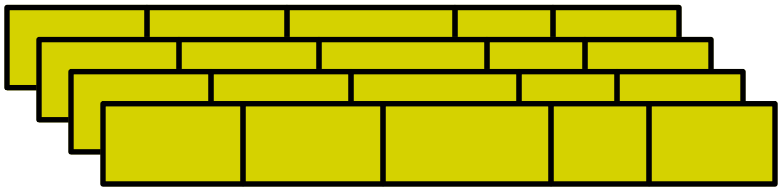
```
SELECT account.account_number,
sum (usage.toll_airtime),
sum (usage.toll_price)
FROM usage, toll, source, account
WHERE usage.toll_id = toll.toll_id
AND usage.source_id = source.source_id
AND usage.account_id = account.account_id
AND toll.type_ind in ('AE'. 'AA')
AND usage.toll_price > 0
AND source.type != 'CIBER'
AND toll.rating_method = 'IS'
AND usage.invoice_date = 20051013
GROUP BY account.account_number
```

	Column-store	*Row-store*
Query 1	*2.06*	*300*
Query 2	*2.20*	*300*
Query 3	*0.09*	*300*
Query 4	*5.24*	*300*
Query 5	*2.88*	*300*

Why? Three main factors (next slides)

Telco example explained (1/3): *read efficiency*

row store



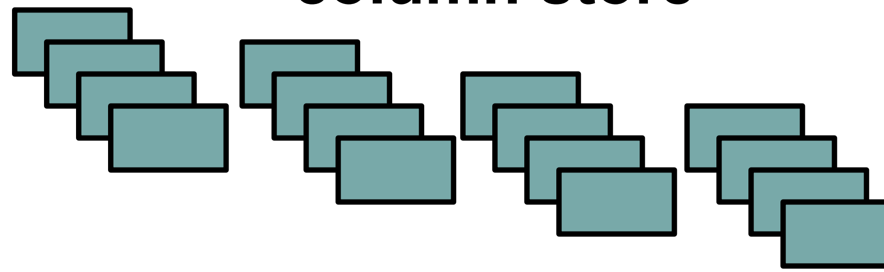
read pages containing entire rows

one row = 212 columns!

is this typical? (it depends)

What about vertical partitioning?
(it does not work with ad-hoc queries)

column store



read only columns needed

in this example: 7 columns

caveats:

- “select * ” not any faster
- clever disk prefetching
- clever tuple reconstruction

Telco example explained (2/3): *compression efficiency*

- Columns compress better than rows
  - Typical row-store compression ratio 1 : 3
  - Column-store 1 : 10
- Why?
  - Rows contain values from different domains
    => more entropy, difficult to dense-pack
  - Columns exhibit significantly less entropy
  - Examples:

    Male, Female, Female, Female, Male
    1998, 1998, 1999, 1999, 1999, 2000

  - Caveat: CPU cost (use lightweight compression)

Telco example explained (3/3): *sorting & indexing efficiency*

- Compression and dense-packing free up space
  - Use multiple overlapping column collections
  - Sorted columns compress better
  - Range queries are faster
  - Use sparse clustered indexes

What about heavily-indexed row-stores?
(works well for single column access,
cross-column joins become increasingly expensive)

Additional opportunities for column-stores

- Block-tuple / vectorized processing
  - Easier to build block-tuple operators
    - Amortizes function-call cost, improves CPU cache performance
  - Easier to apply vectorized primitives
    - Software-based: bitwise operations
    - Hardware-based: SIMD

Part 3

- Opportunities with compressed columns
  - *Avoid* decompression: operate directly on compressed
  - *Delay* decompression (and tuple reconstruction)
    - Also known as: *late materialization*

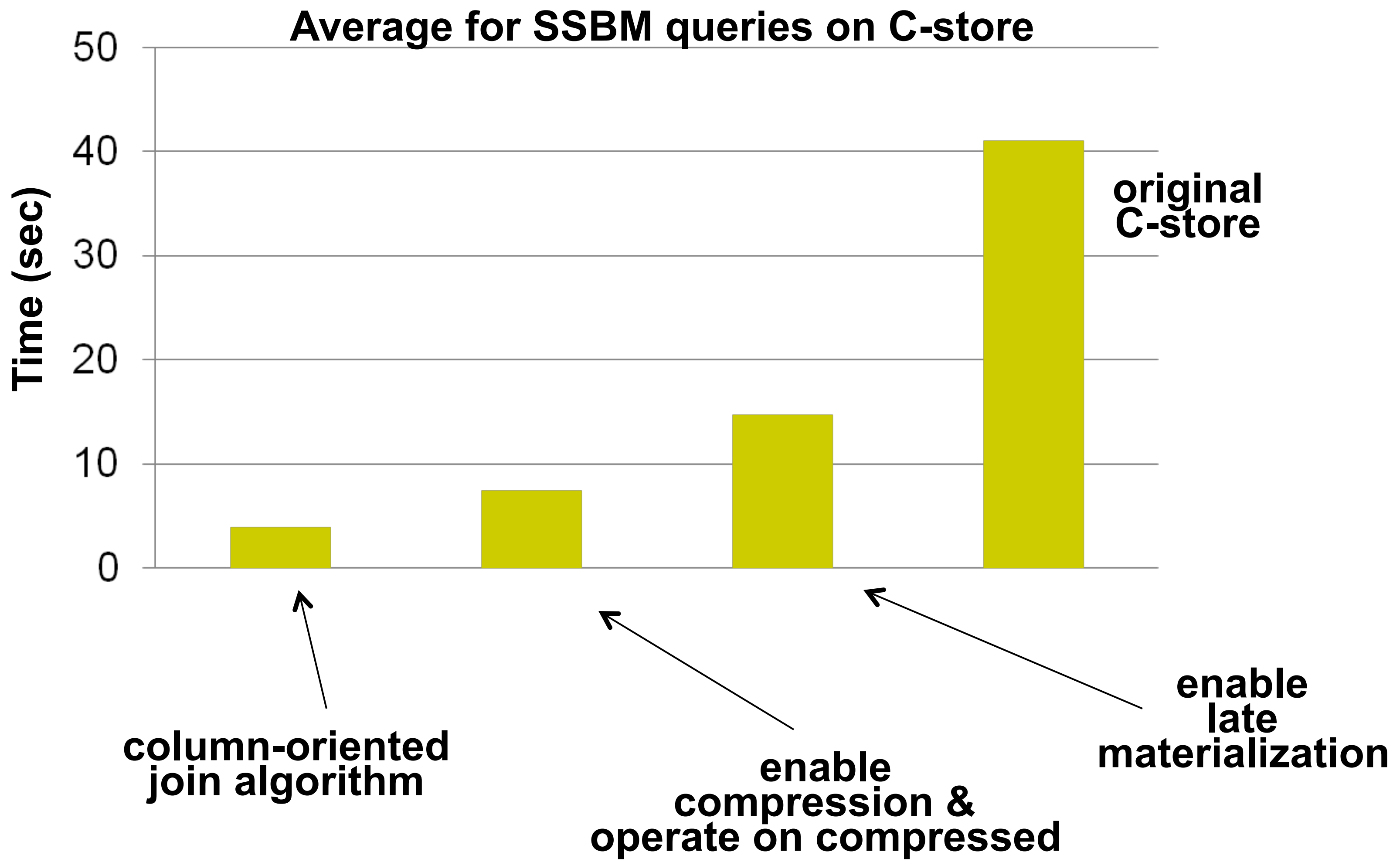
more in Part 2

- Exploit columnar storage in other DBMS components
  - Physical design (both static and dynamic)

See: *Database Cracking*, from CWI

Effect on C-Store performance

"Column-Stores vs Row-Stores: How Different are They Really?" Abadi, Hachem, and Madden. SIGMOD 2008.



Summary of column-store key features

- Storage layout
  - columnar storage — Part 1
  - header/ID elimination — Part 1
  - compression — Part 2, Part 3
  - multiple sort orders
- Execution engine
  - column operators — Part 1, Part 2
  - avoid decompression — Part 2
  - late materialization — Part 2
  - vectorized operations — Part 3
- Design tools, optimizer

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From DSM to Column-stores

70s -1985:

TOD: Time Oriented Database – Wiederhold et al.
"A Modular, Self-Describing Clinical Databank System,"
Computers and Biomedical Research, 1975
More 1970s: Transposed files, Lorie, Batory, Svensson.

"An overview of cantor: a new system for data analysis"
Karasalo, Svensson, SSDBM 1983

1985: DSM paper

"A decomposition storage model"
Copeland and Khoshafian. SIGMOD 1985.

1990s: Commercialization through SybaseIQ

Late 90s – 2000s: Focus on main-memory performance

- DSM "on steroids" [1997 – now] — CWI: MonetDB
- Hybrid DSM/NSM [2001 – 2004] — Wisconsin: PAX, Fractured Mirrors

Michigan: Data Morphing

CMU: Clotho

2005 – : Re-birth of read-optimized DSM as "column-store"

MIT: C-Store

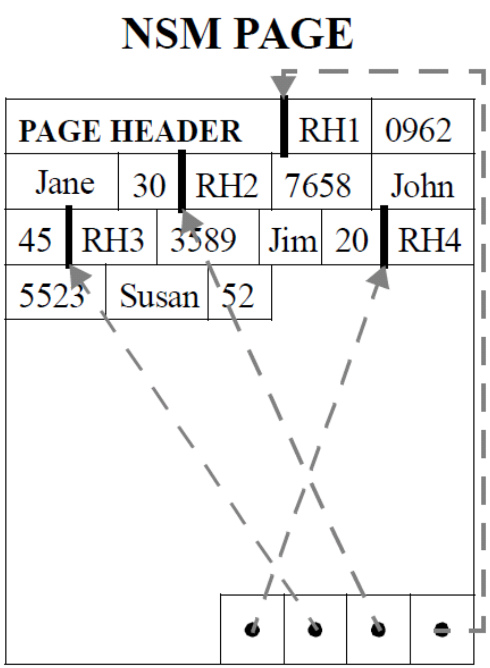
CWI: MonetDB/X100

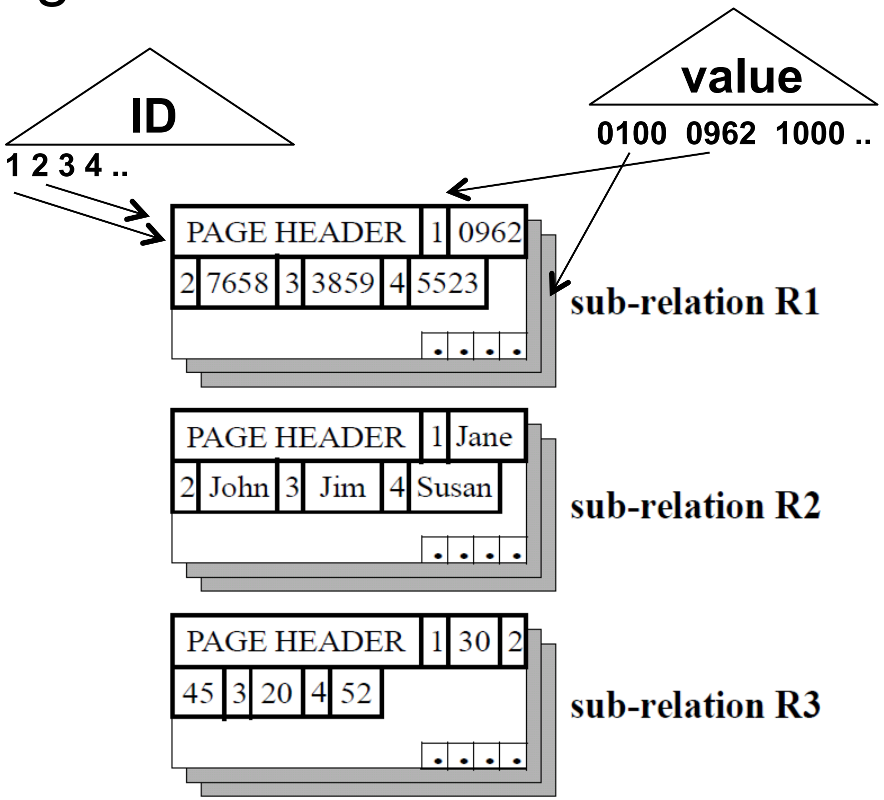
10+ startups

The original DSM paper

"A decomposition storage model" Copeland and Khoshafian. SIGMOD 1985.

- Proposed as an alternative to NSM
- 2 indexes: clustered on ID, non-clustered on value
- Speeds up queries projecting few columns
- Requires more storage





Memory wall and PAX

- 90s: Cache-conscious research

from: "Cache Conscious Algorithms for Relational Query Processing." Shatdal, Kant, Naughton. VLDB 1994.

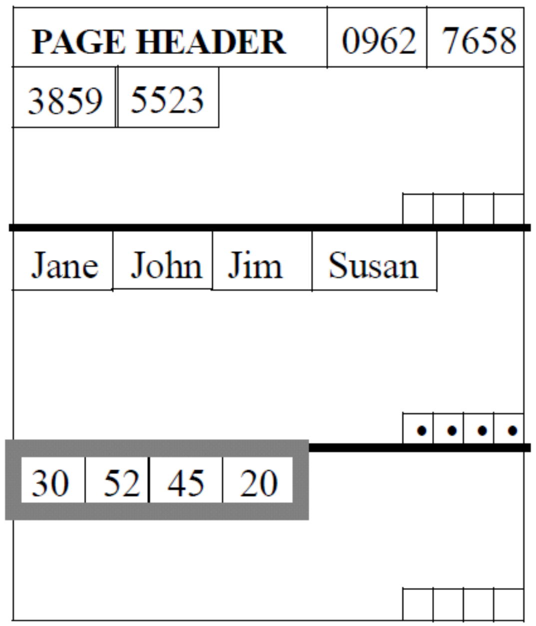
to: "Database Architecture Optimized for the New Bottleneck: Memory Access." Boncz, Manegold, Kersten. VLDB 1999.

and: "DBMSs on a modern processor: Where does time go?" Ailamaki, DeWitt, Hill, Wood.

- PAX: Partition Attributes Across
  - Retains NSM I/O pattern
  - Optimizes cache-to-RAM communication

"Weaving Relations for Cache Performance." Ailamaki, DeWitt, Hill, Skounakis, VLDB 2001.

PAX PAGE



More hybrid NSM/DSM schemes

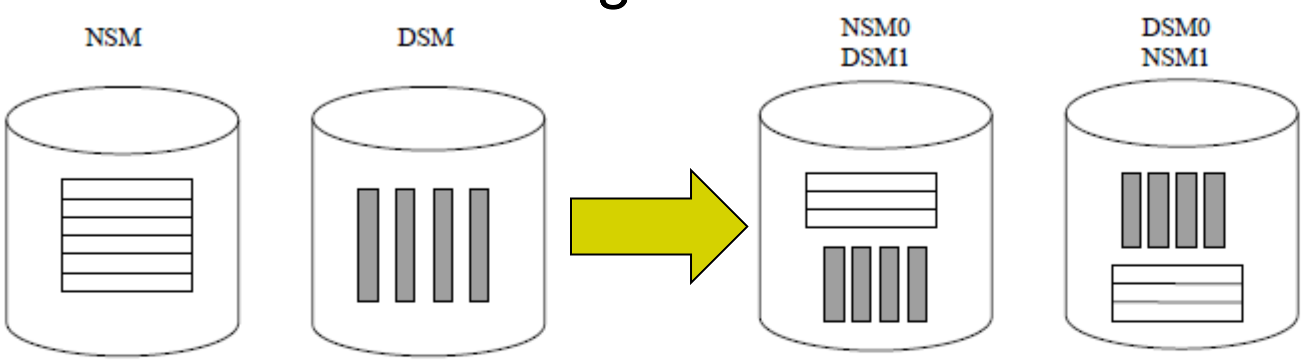
- Dynamic PAX: Data Morphing

> "Data morphing: an adaptive, cache-conscious storage technique." Hankins, Patel, VLDB 2003.

- Clotho: custom layout using scatter-gather I/O

> "Clotho: Decoupling Memory Page Layout from Storage Organization." Shao, Schindler, Schlosser, Ailamaki, and Ganger. VLDB 2004.

- Fractured mirrors
  - Smart mirroring with both NSM/DSM copies



> "A Case For Fractured Mirrors." Ramamurthy, DeWitt, Su, VLDB 2002.

MonetDB (more in Part 3)

- Late 1990s, CWI: Boncz, Manegold, and Kersten
- Motivation:
  - Main-memory
  - Improve computational efficiency by avoiding expression interpreter
  - DSM with virtual IDs natural choice
  - Developed new query execution algebra
- Initial contributions:
  - Pointed out memory-wall in DBMSs
  - Cache-conscious projections and joins
  - …

2005: the (re)birth of column-stores

- New hardware and application realities
  - Faster CPUs, larger memories, disk bandwidth limit
  - Multi-terabyte Data Warehouses
- New approach: combine several techniques
  - Read-optimized, fast multi-column access, disk/CPU efficiency, light-weight compression
- C-store paper:
  - First comprehensive design description of a column-store
- MonetDB/X100
  - "proper" disk-based column store
- Explosion of new products

Performance tradeoffs: columns vs. rows

DSM traditionally was not favored by technology trends
How has this changed?

- Optimized DSM in "Fractured Mirrors," 2002
- "Apples-to-apples" comparison

  "Performance Tradeoffs in Read-Optimized Databases" Harizopoulos, Liang, Abadi, Madden, VLDB' 06

- Follow-up study

  "Read-Optimized Databases, In-Depth" Holloway, DeWitt, VLDB' 08

- Main-memory DSM vs. NSM

  "DSM vs. NSM: CPU performance tradeoffs in block-oriented query processing" Boncz, Zukowski, Nes, DaMoN' 08

- Flash-disks: a come-back for PAX?

  "Fast Scans and Joins Using Flash Drives" Shah, Harizopoulos, Wiener, Graefe. DaMoN' 08

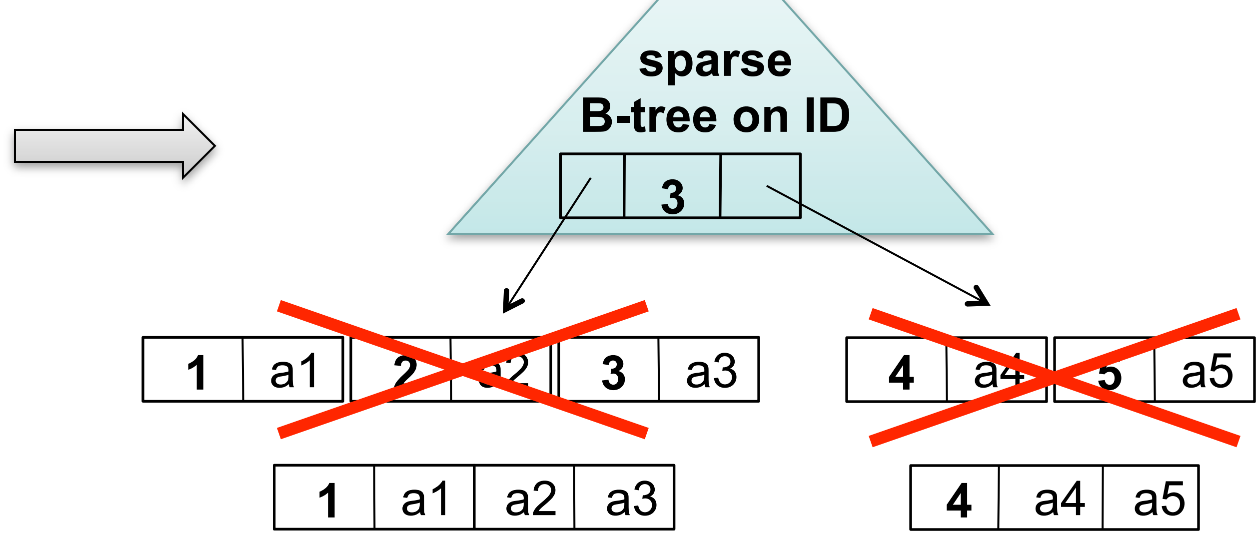
  "Query Processing Techniques for Solid State Drives" Tsirogiannis, Harizopoulos, Shah, Wiener, Graefe, SIGMOD' 09

Fractured mirrors: a closer look

- Store DSM relations inside a B-tree
  - Leaf nodes contain values
  - Eliminate IDs, amortize header overhead
  - Custom implementation on Shore

"A Case For Fractured Mirrors" Ramamurthy, DeWitt, Su, VLDB 2002.

Tuple Header	TID	Column Data
	1	a1
	2	a2
	3	a3
	4	a4
	5	a5

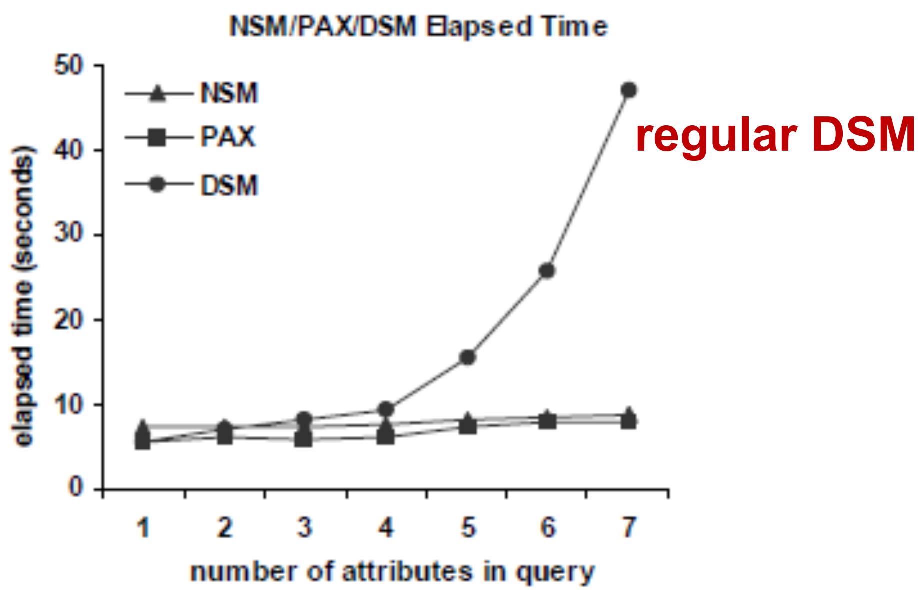


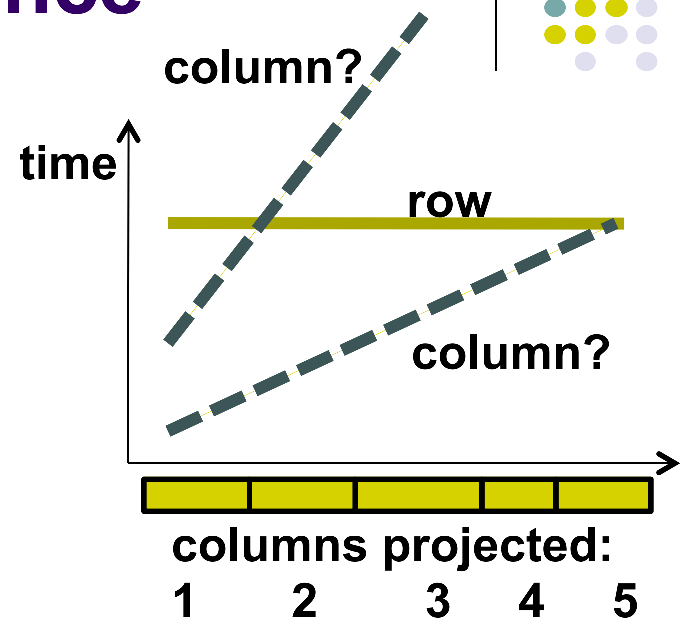
Similar: storage density comparable to column stores

"Efficient columnar storage in B-trees" Graefe. Sigmod Record 03/2007.

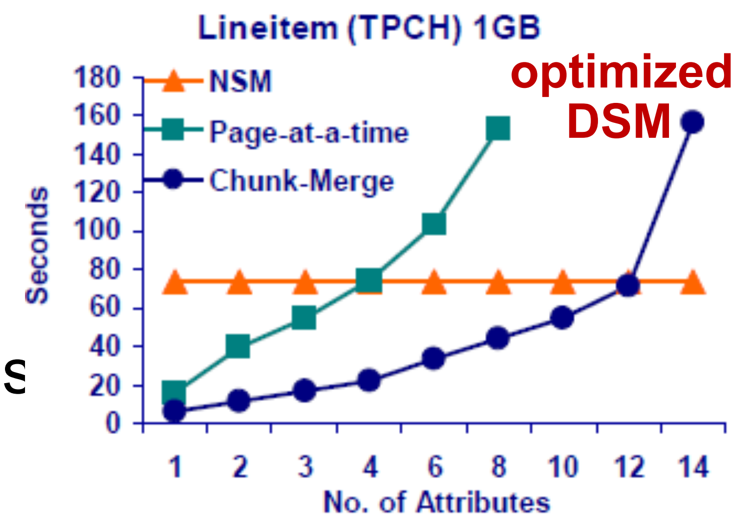
Fractured mirrors: performance

From PAX paper:



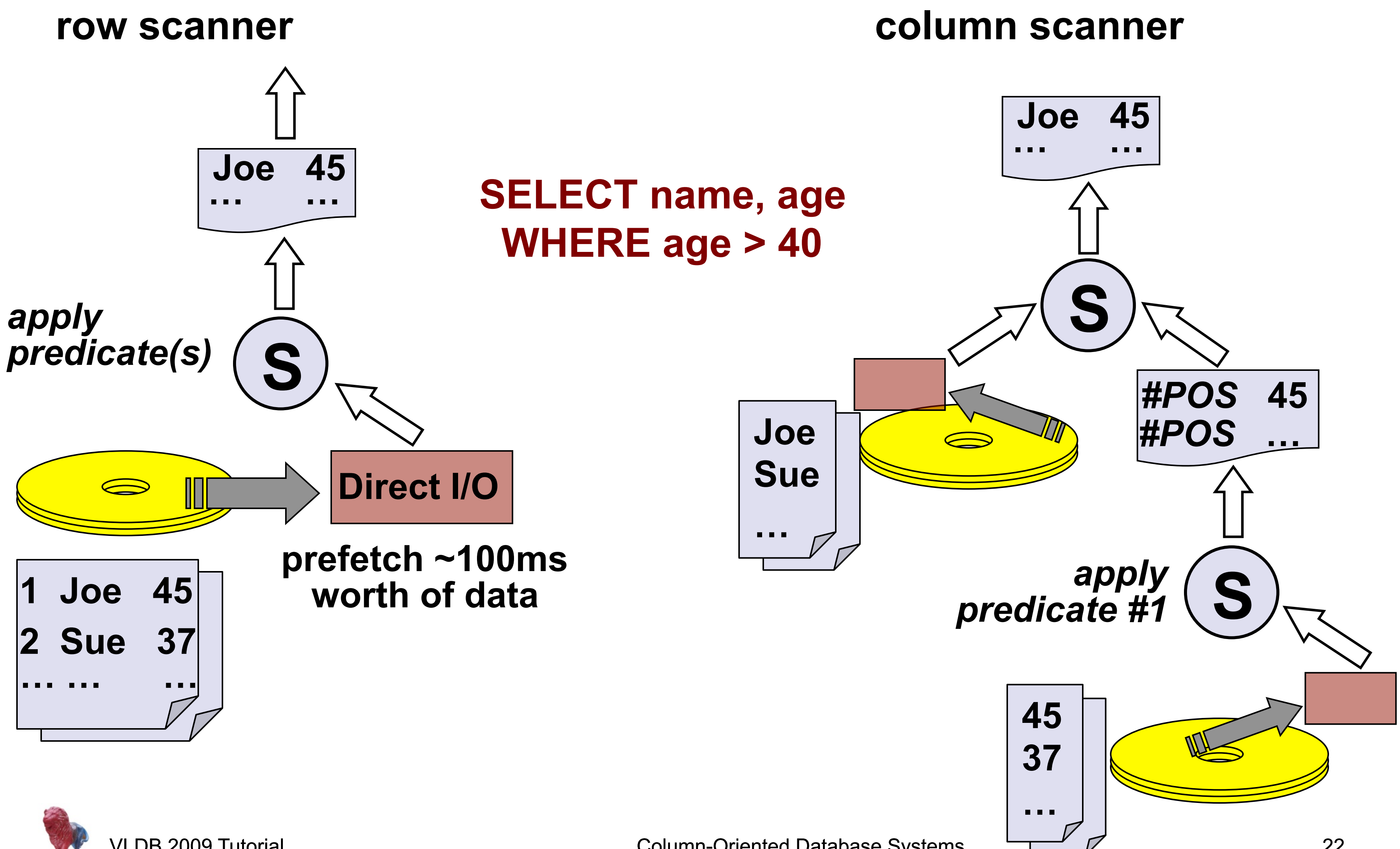


- Chunk-based tuple merging
  - Read in segments of M pages
  - Merge segments in memory
  - Becomes CPU-bound after 5 pages



Column-scanner implementation

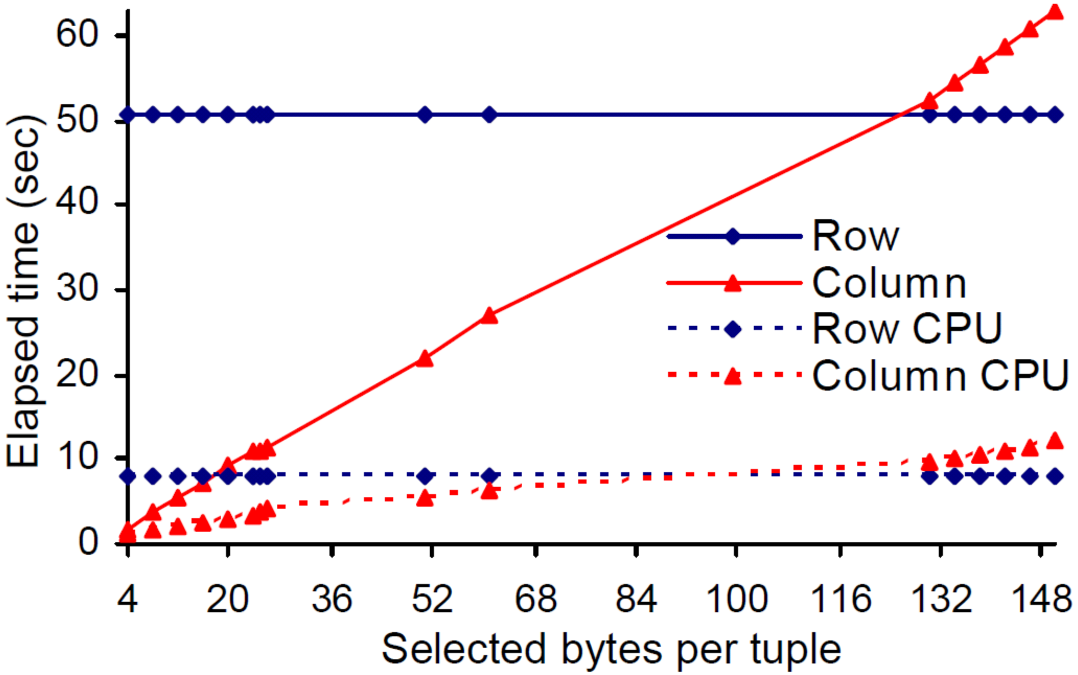
"Performance Tradeoffs in Read-Optimized Databases"
Harizopoulos, Liang, Abadi, Madden, VLDB' 06



Scan performance

- Large prefetch hides disk seeks in columns
- Column-CPU efficiency with lower selectivity
- Row-CPU suffers from memory stalls
- Memory stalls disappear in narrow tuples
- Compression: similar to narrow

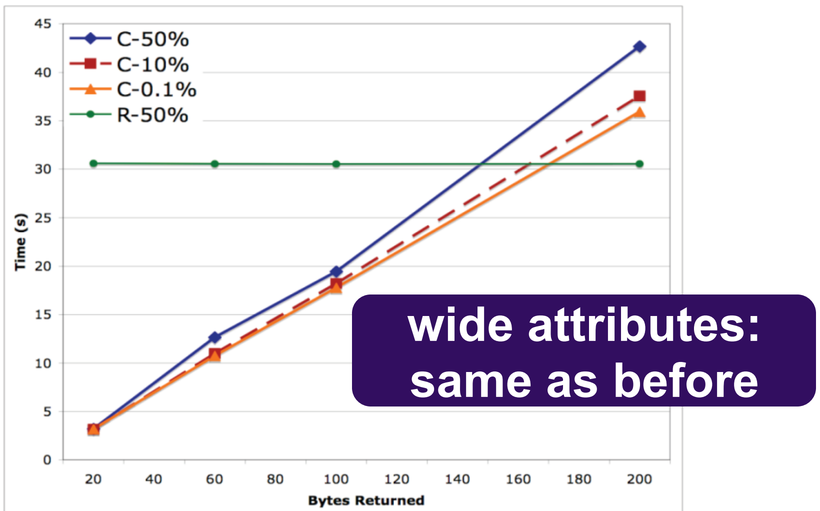
not shown, details in the paper

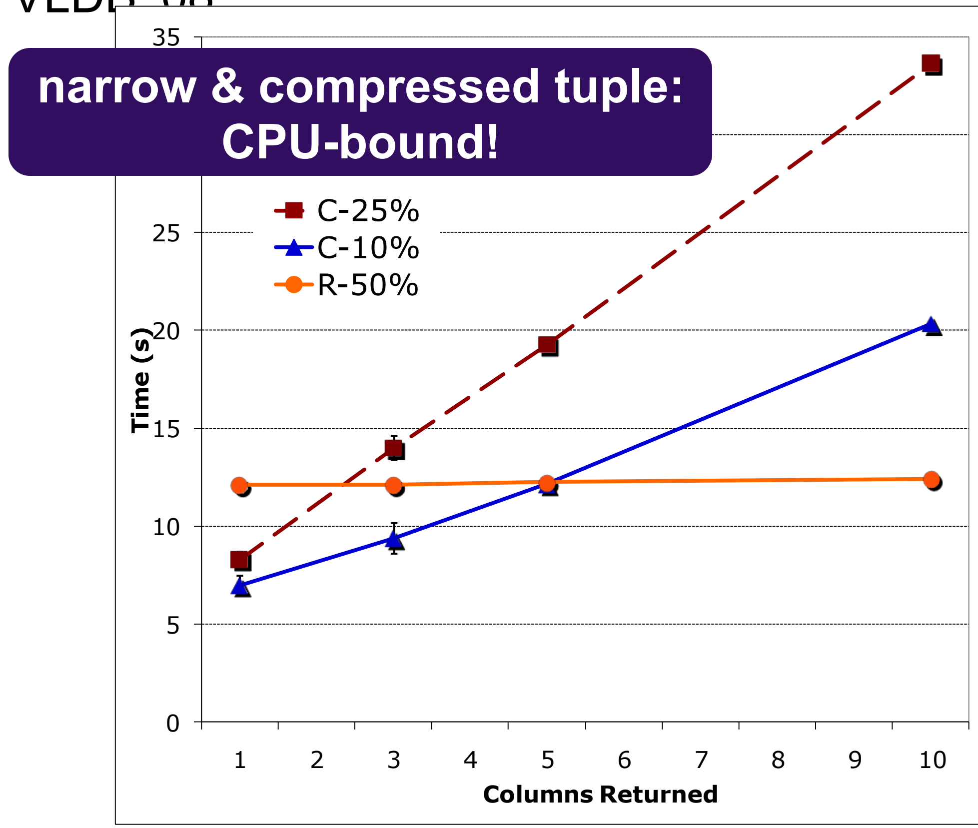


Even more results

"Read-Optimized Databases, In-Depth" Holloway, DeWitt, VLDB' 08

- Same engine as before
- Additional findings





Non-selective queries, narrow tuples, favor well-compressed rows

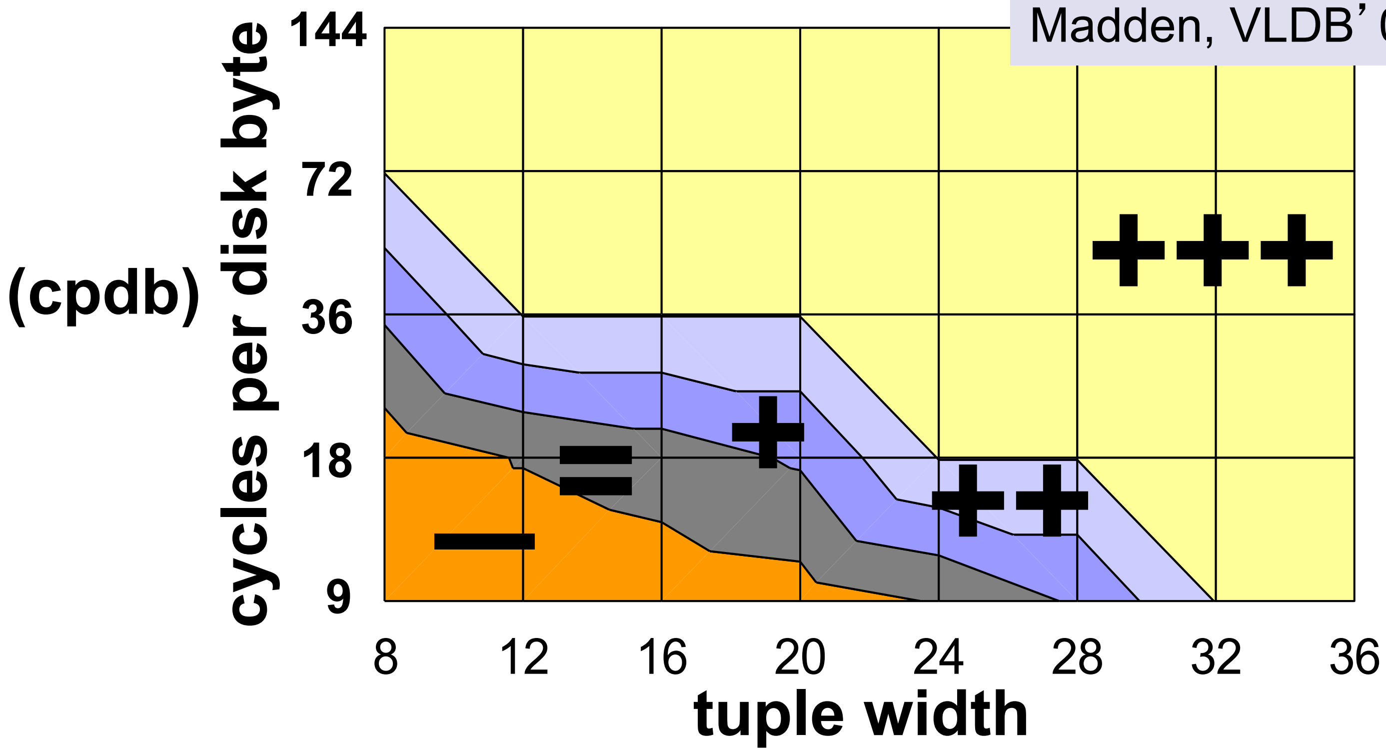
Materialized views are a win

Scan times determine early materialized joins

Column-joins are covered in part 2!

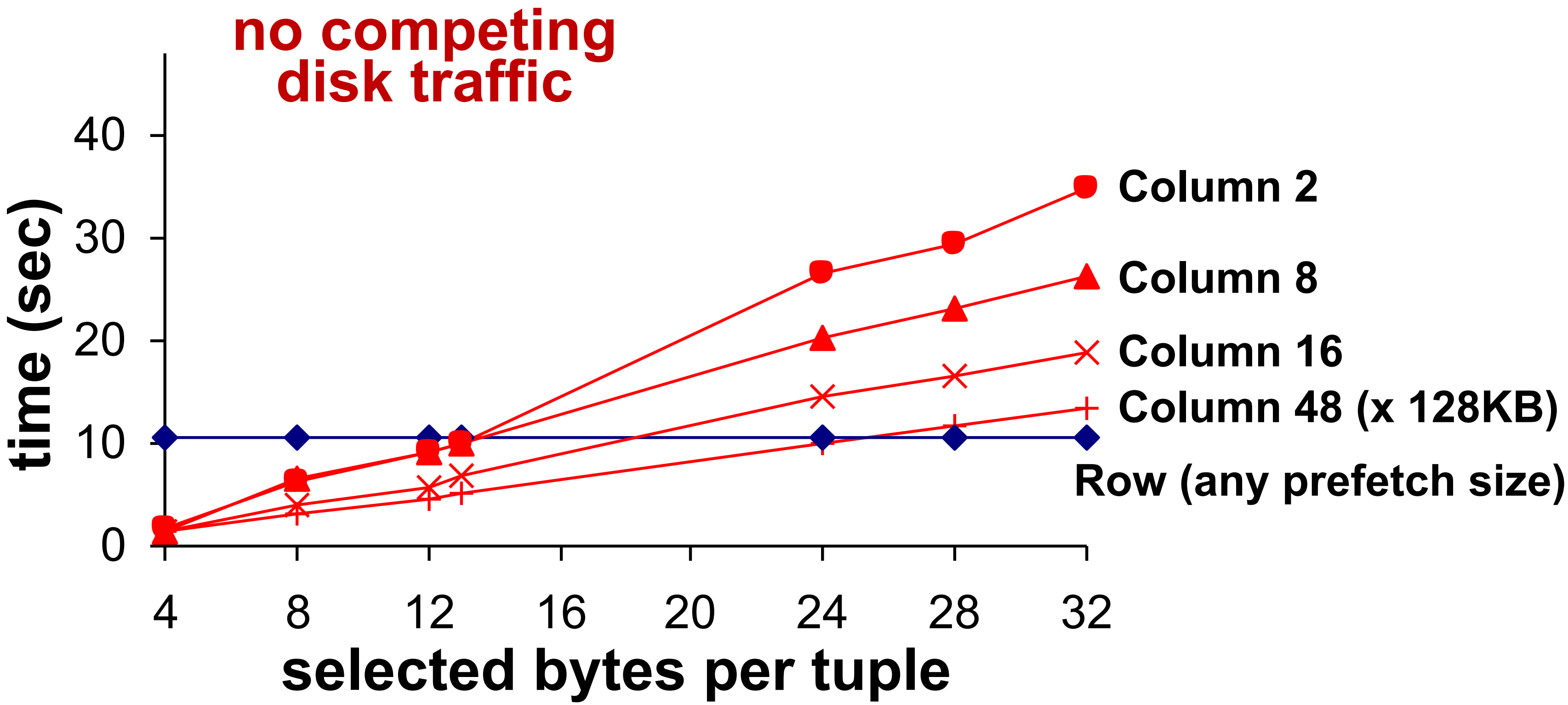
Speedup of columns over rows

"Performance Tradeoffs in Read-Optimized Databases"
Harizopoulos, Liang, Abadi, Madden, VLDB' 06



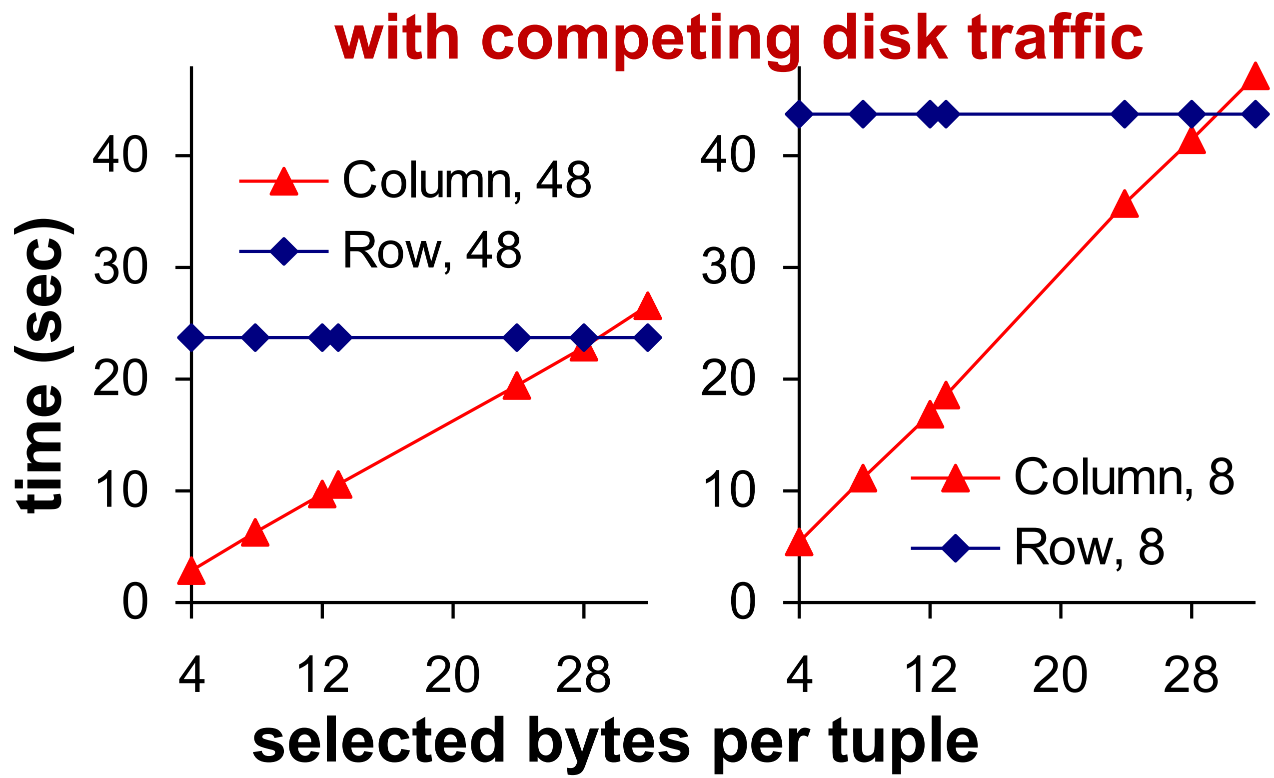
- Rows favored by narrow tuples and low *cpdb*
  - Disk-bound workloads have higher *cpdb*

Varying prefetch size



- No prefetching hurts columns in single scans

Varying prefetch size



- No prefetching hurts columns in single scans
- Under competing traffic, columns outperform rows for any prefetch size

CPU Performance

"DSM vs. NSM: CPU performance trade offs in block-oriented query processing"
Boncz, Zukowski, Nes, DaMoN' 08

- Benefit in on-the-fly conversion between NSM and DSM
- DSM: sequential access (block fits in L2), random in L1
- NSM: random access, SIMD for grouped Aggregation

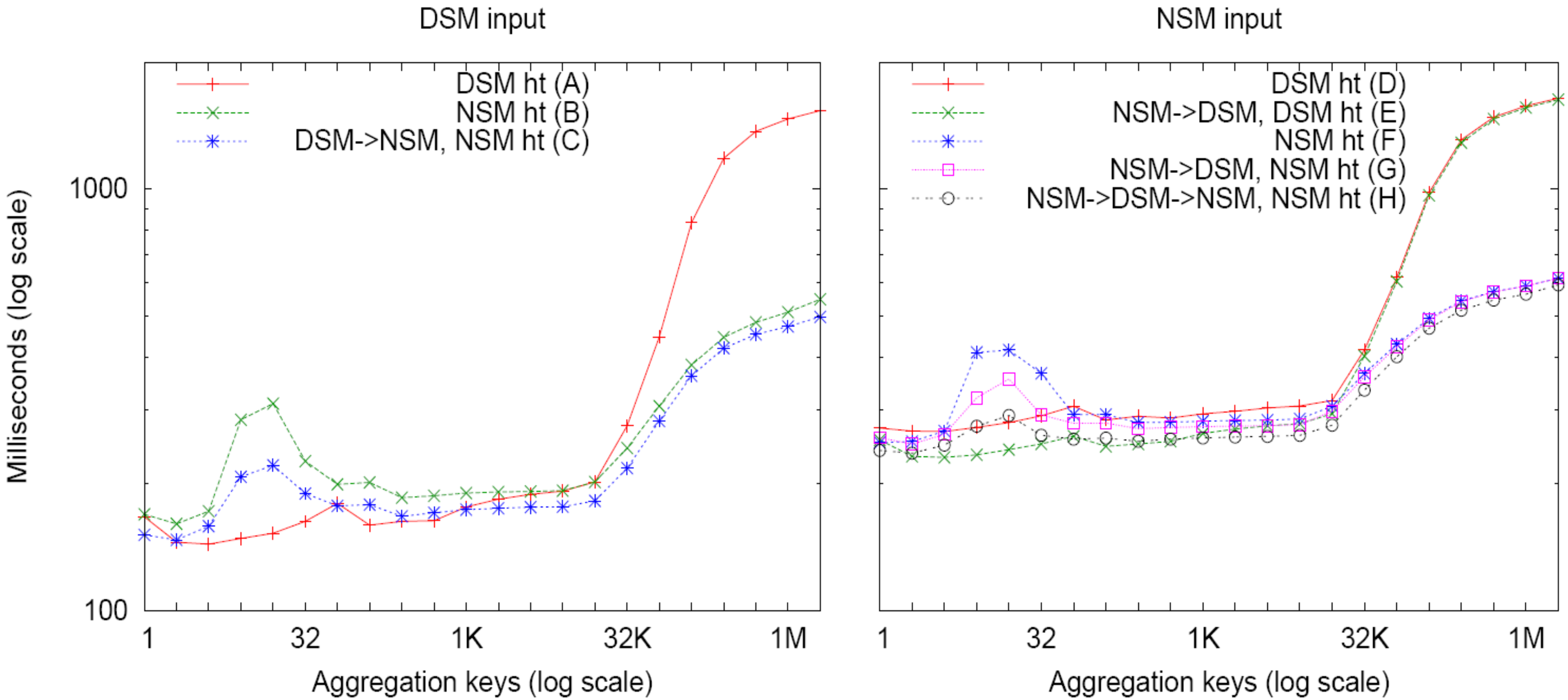


Figure 5: TPC-H Q1, with a varying number of keys and different data organizations (ht – hash table)

New storage technology: Flash SSDs

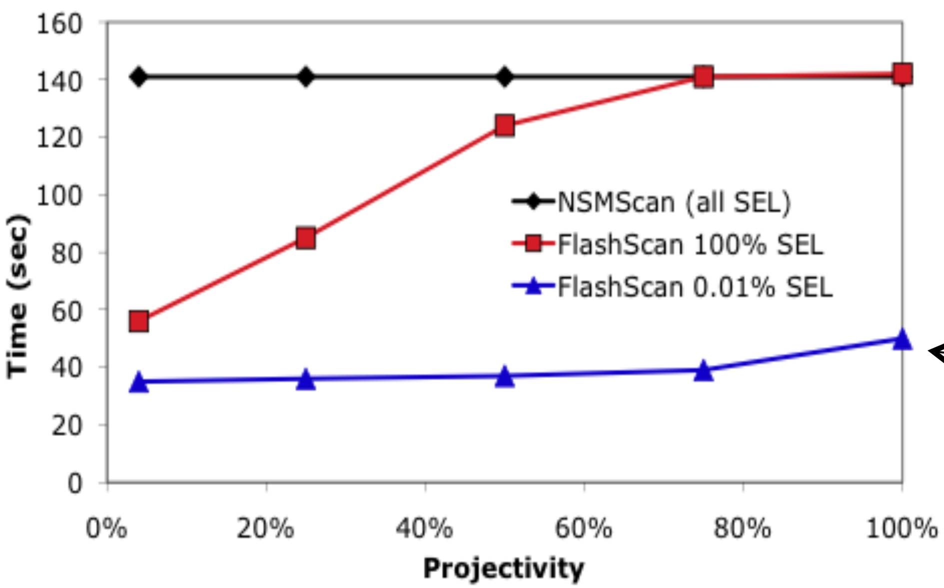
- Performance characteristics
  - very fast random reads, slow random writes
  - fast sequential reads and writes
- Price per bit (capacity follows)
  - cheaper than RAM, order of magnitude more expensive than Disk
- Flash Translation Layer introduces unpredictability
  - avoid random writes!
- Form factors not ideal yet
  - SSD (➔ small reads still suffer from SATA overhead/OS limitations)
  - PCI card (➔ high price, limited expandability)

- Boost Sequential I/O in a simple package
  - Flash RAID: very tight bandwidth/cm^3 packing (4GB/sec inside the box)
- Column Store Updates
  - useful for delta structures and logs
- Random I/O on flash fixes unclustered index access
  - still suboptimal if I/O block size > record size
  - therefore column stores profit mush less than horizontal stores
- Random I/O useful to exploit secondary, tertiary table orderings
  - the larger the data, the deeper clustering one can exploit

Even faster column scans on flash SSDs

- New-generation SSDs
  - Very fast random reads, slower random writes
  - Fast sequential RW, comparable to HDD arrays
- No expensive seeks across columns
- FlashScan and Flashjoin: PAX on SSDs, inside Postgres

30K Read IOps, 3K Write Iops
250MB/s Read BW, 200MB/s Write

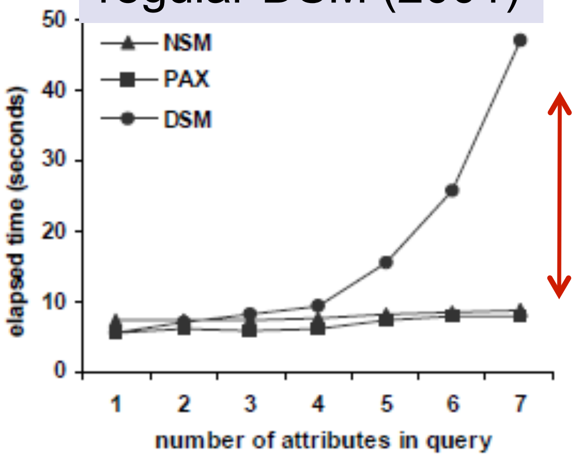


"Query Processing Techniques for Solid State Drives" Tsirogiannis, Harizopoulos, Shah, Wiener, Graefe, SIGMOD'09

mini-pages with no qualified attributes are not accessed

Column-scan performance over time

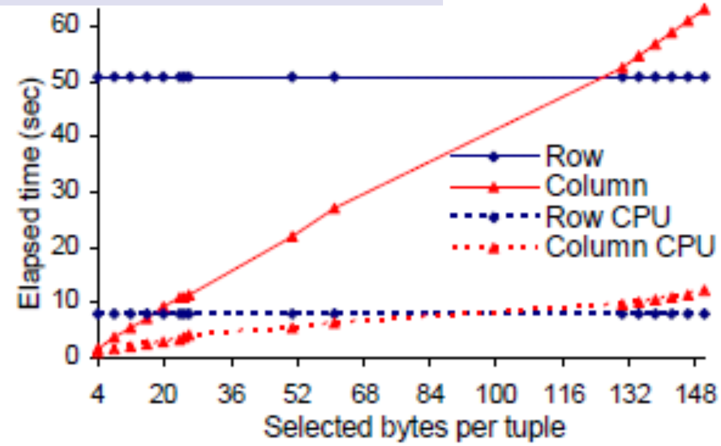
regular DSM (2001)

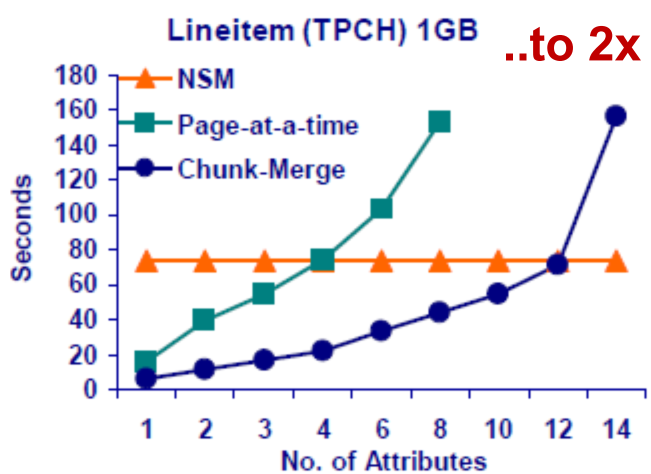


from 7x slower

column-store (2006)

..to 1.2x slower

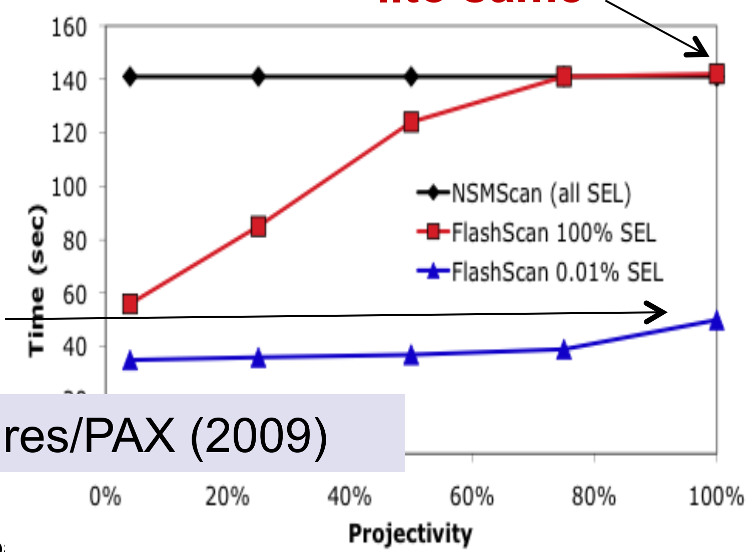




..to 2x slower

..to same

and 3x faster!



optimized DSM (2002)

SSD Postgres/PAX (2009)

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Architecture of a column-store

storage layout

- read-optimized: dense-packed, compressed
- organize in extends, batch updates
- multiple sort orders
- sparse indexes

engine

- block-tuple operators
- new access methods
- optimized relational operators

system-level

- system-wide column support
- loading / updates
- scaling through multiple nodes
- transactions / redundancy

C-Store

"C-Store: A Column-Oriented DBMS." Stonebraker et al. VLDB 2005.

- Compress columns
- No alignment
- Big disk blocks
- Only materialized views (perhaps many)
- Focus on Sorting not indexing
- Data ordered on anything, not just time
- Automatic physical DBMS design
- Optimize for grid computing
- Innovative redundancy
- Xacts – but no need for Mohan
- Column optimizer and executor

C-Store: only materialized views (MVs)

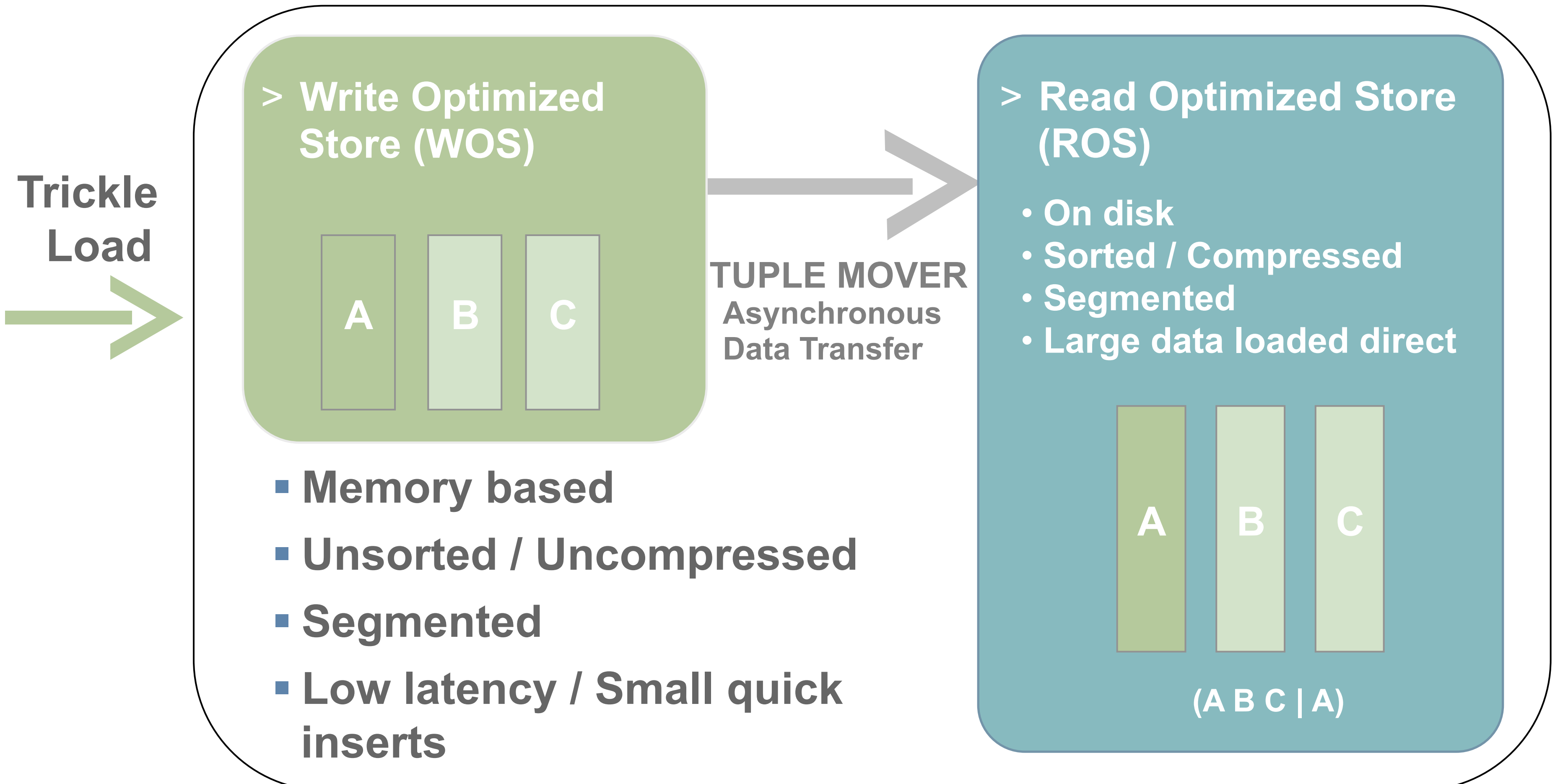
- Projection (MV) is some number of columns from a fact table
- Plus columns in a dimension table – with a 1-n join between Fact and Dimension table
- Stored in order of a storage key(s)
- Several may be stored!
- With a permutation, if necessary, to map between them
- Table (as the user specified it and sees it) is not stored!
- No secondary indexes (they are a one column sorted MV plus a permutation, if you really want one)

User view:
EMP (name, age, salary, dept)
Dept (dname, floor)

Possible set of MVs:
MV-1 (name, dept, floor) in floor order
MV-2 (salary, age) in age order
MV-3 (dname, salary, name) in salary order

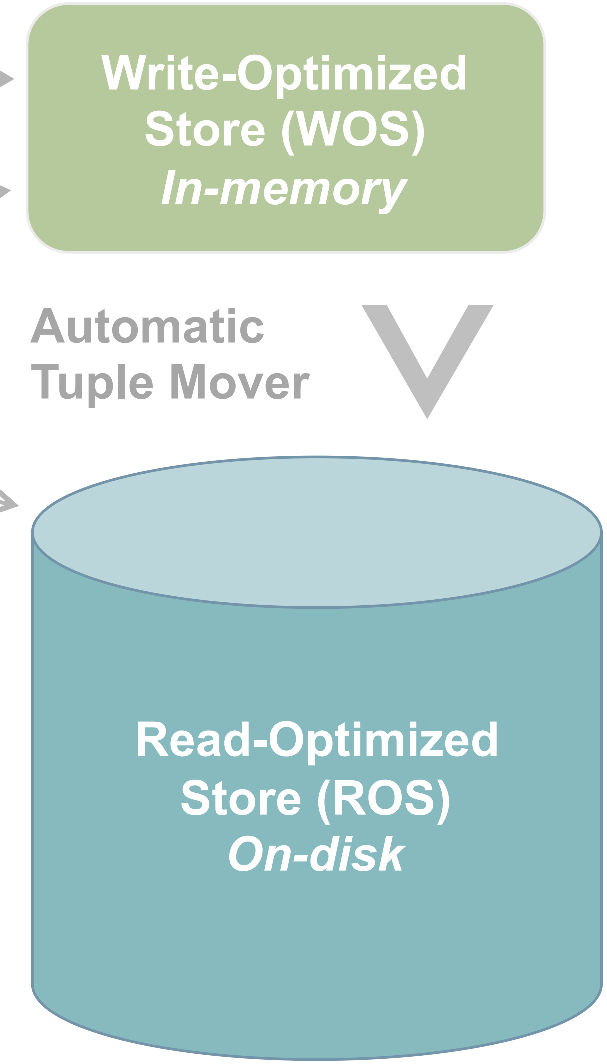
Continuous Load and Query (Vertica)

Hybrid Storage Architecture



Loading Data (Vertica)

- INSERT, UPDATE, DELETE
- Bulk and Trickle Loads
  - COPY
  - COPY DIRECT
- User loads data into logical Tables
- Vertica loads atomically into storage



Applications for column-stores

- Data Warehousing
  - High end (clustering)
  - Mid end/Mass Market
  - Personal Analytics
- Data Mining
  - E.g. Proximity
- Google BigTable
- RDF
  - Semantic web data management
- Information retrieval
  - Terabyte TREC
- Scientific datasets
  - SciDB initiative
  - SLOAN Digital Sky Survey on MonetDB

List of column-store systems

- Cantor (history)
- Sybase IQ
- SenSage (former Addamark Technologies)
- Kdb
- 1010data
- MonetDB
- C-Store/Vertica
- X100/VectorWise
- KickFire
- SAP Business Accelerator
- Infobright
- ParAccel
- Exasol

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Simulate a Column-Store inside a Row-Store

Date	Store	Product	Customer	Price
01/01	BOS	Table	Mesa	$20
01/01	NYC	Chair	Lutz	$13
01/01	BOS	Bed	Mudd	$79

Option A: Vertical Partitioning

Date

TID	Value
1	01/01
2	01/01
3	01/01

Store

TID	Value
1	BOS
2	NYC
3	BOS

Product

TID	Value
1	Table
2	Chair
3	Bed

Customer

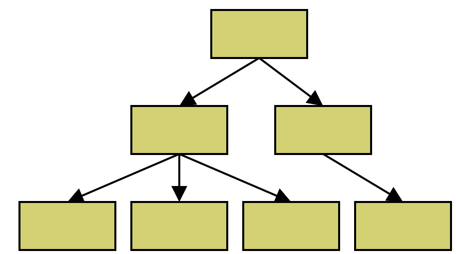
TID	Value
1	Mesa
2	Lutz
3	Mudd

Price

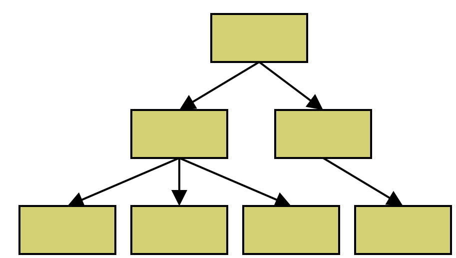
TID	Value
1	$20
2	$13
3	$79

Option B: Index Every Column

Date Index



Store Index



...

Simulate a Column-Store inside a Row-Store

Date	Store	Product	Customer	Price
01/01	BOS	Table	Mesa	$20
01/01	NYC	Chair	Lutz	$13
01/01	BOS	Bed	Mudd	$79

Option A: Vertical Partitioning

Date

Value	StartPos	Length
01/01	1	3

Store

TID	Value
1	BOS
2	NYC
3	BOS

Product

TID	Value
1	Table
2	Chair
3	Bed

Customer

TID	Value
1	Mesa
2	Lutz
3	Mudd

Price

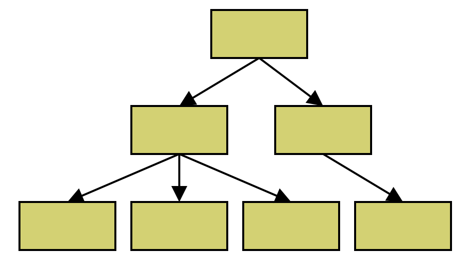
TID	Value
1	$20
2	$13
3	$79

Can explicitly run-length encode date

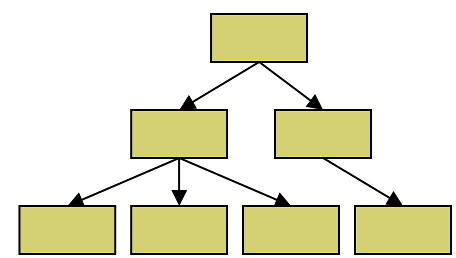
"Teaching an Old Elephant New Tricks." Bruno, CIDR 2009.

Option B: Index Every Column

Date Index



Store Index



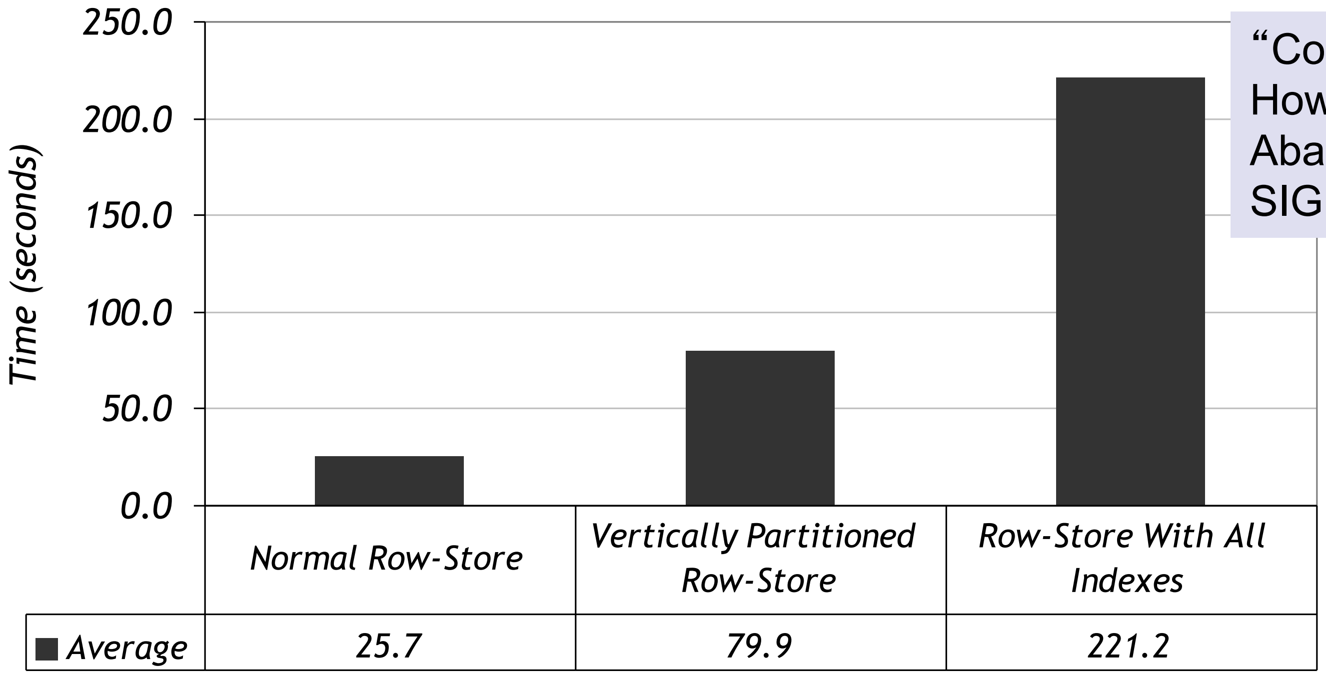
…

Experiments

- Star Schema Benchmark (SSBM)

Adjoined Dimension Column Index (ADC Index) to Improve Star Schema Query Performance”. O’ Neil et. al. ICDE 2008.

- Implemented by professional DBA
- Original row-store plus 2 column-store simulations on same row-store product



“Column-Stores vs Row-Stores: How Different are They Really?” Abadi, Hachem, and Madden. SIGMOD 2008.

What's Going On? Vertical Partitions

- Vertical partitions in row-stores:
  - Work well when workload is known
  - ..and queries access disjoint sets of columns
  - See automated physical design
- Do not work well as full-columns
  - TupleID overhead significant
  - Excessive joins

Tuple Header	TID	Column Data
	1	
	2	
	3	

Queries touch 3-4 foreign keys in fact table, 1-2 numeric columns

Complete fact table takes up ~4 GB (compressed)

Vertically partitioned tables take up 0.7-1.1 GB (compressed)

"Column-Stores vs. Row-Stores: How Different Are They Really?" Abadi, Madden, and Hachem. SIGMOD 2008.

What's Going On? All Indexes Case

- Tuple construction
  - Common type of query:

```
SELECT store_name, SUM(revenue)
FROM Facts, Stores
WHERE fact.store_id = stores.store_id
    AND stores.country = "Canada"
GROUP BY store_name
```

  - Result of lower part of query plan is a set of TIDs that passed all predicates
  - Need to extract SELECT attributes at these TIDs
    - BUT: index maps value to TID
    - You really want to map TID to value (i.e., a vertical partition)

→ Tuple construction is SLOW

So….

- All indexes approach is a poor way to simulate a column-store
- Problems with vertical partitioning are NOT fundamental
  - Store tuple header in a separate partition
  - Allow virtual TIDs
  - Combine clustered indexes, vertical partitioning
- So can row-stores simulate column-stores?
  - Might be possible, BUT:
    - Need better support for vertical partitioning at the storage layer
    - Need support for column-specific optimizations at the executer level
    - Full integration: buffer pool, transaction manager, ..
  - When will this happen?
    - Most promising features = soon
    - ..unless new technology / new objectives change the game (SSDs, Massively Parallel Platforms, Energy-efficiency)

See Part 2, Part 3 for most promising features

End of Part 1

- Basic concepts — *Stavros*
  - Introduction to key features
  - From DSM to column-stores and performance tradeoffs
  - Column-store architecture overview
  - Will rows and columns ever converge?
- Part 2: Column-oriented execution — *Daniel*
- Part 3: MonetDB/X100 and CPU efficiency — *Peter*

Part 2 Outline

- Compression
- Tuple Materialization
- Joins

Column-Oriented Database Systems

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Compression

“Super-Scalar RAM-CPU Cache Compression” Zukowski, Heman, Nes, Boncz, ICDE’06

“Integrating Compression and Execution in Column-Oriented Database Systems” Abadi, Madden, and Ferreira, SIGMOD ’06

•Query optimization in compressed database systems” Chen, Gehrke, Korn, SIGMOD’01

Compression

- **Trades I/O for CPU**
- **Increased column-store opportunities:**
  - **Higher data value locality in column stores**
  - **Techniques such as run length encoding far more useful**
  - **Can use extra space to store multiple copies of data in different sort orders**

Run-length Encoding

Quarter	Product ID	Price
Q1	1	5
Q1	1	7
Q1	1	2
Q1	1	9
Q1	1	6
Q1	2	8
Q1	2	5
…	…	…
Q2	1	3
Q2	1	8
Q2	1	1
Q2	2	4
…	…	…

→

Quarter

(value, start_pos, run_length)

(Q1, 1, 300)
(Q2, 301, 350)
(Q3, 651, 500)
(Q4, 1151, 600)

Product ID

(value, start_pos, run_length)

(1, 1, 5)
(2, 6, 2)
…
(1, 301, 3)
(2, 304, 1)
…

Price

5
7
2
9
6
8
5
…
3
8
1
4
…

Bit-vector Encoding

- **For each unique value, v, in column c, create bit-vector b**
  - **b[i] = 1 if c[i] = v**
- **Good for columns with few unique values**
- **Each bit-vector can be further compressed if sparse**

Product ID		ID: 1	ID: 2	ID: 3	…
1		1	0	0	0
1		1	0	0	0
1		1	0	0	0
1		1	0	0	0
1	→	1	0	0	0
2		0	1	0	0
2		0	1	0	0
…		…	…	…	…
1		1	0	0	0
1		1	0	0	0
2		0	1	0	0
3		0	0	1	0
…		…	…	…	…

Dictionary Encoding

- **For each unique value create dictionary entry**
- **Dictionary can be per-block or per-column**
- **Column-stores have the advantage that dictionary entries may encode multiple values at once**

Quarter
Q1
Q2
Q4
Q1
Q3
Q1
Q1
Q1
Q2
Q4
Q3
Q3
…

→

Quarter
0
1
3
0
2
0
0
0
1
3
2
2

+

Dictionary

0: Q1
1: Q2
2: Q3
3: Q4

OR

Quarter
24
128
122

+

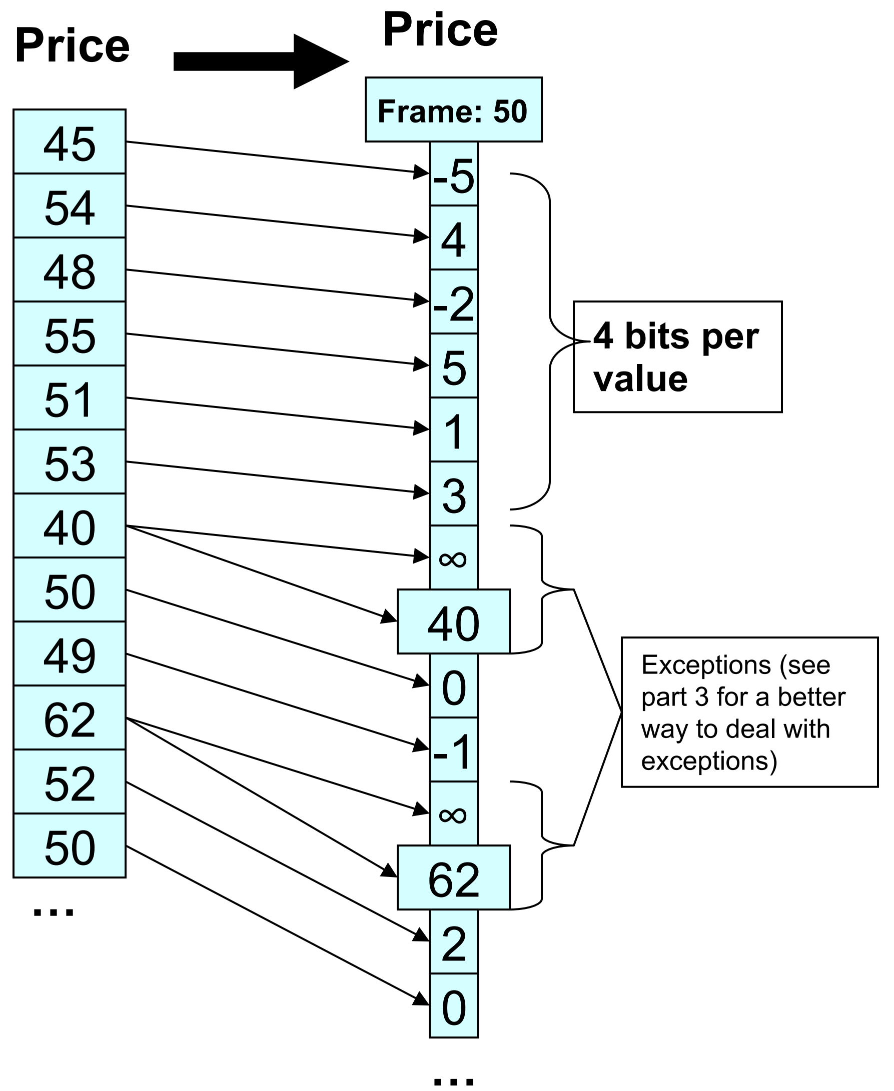
Dictionary

24: Q1, Q2, Q4, Q1
…
122: Q2, Q4, Q3, Q3
…
128: Q3, Q1, Q1, Q1

Frame Of Reference Encoding

- **Encodes values as b bit offset from chosen frame of reference**
- **Special escape code (e.g. all bits set to 1) indicates a difference larger than can be stored in b bits**
  - **After escape code, original (uncompressed) value is written**

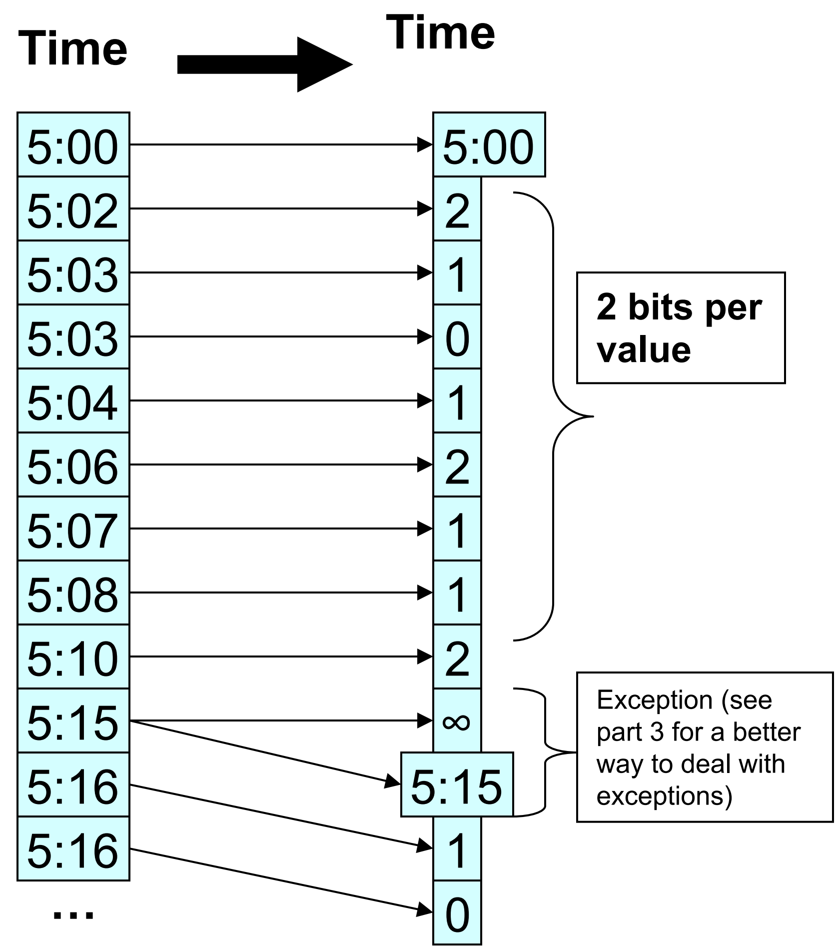
"Compressing Relations and Indexes" Goldstein, Ramakrishnan, Shaft, ICDE'98



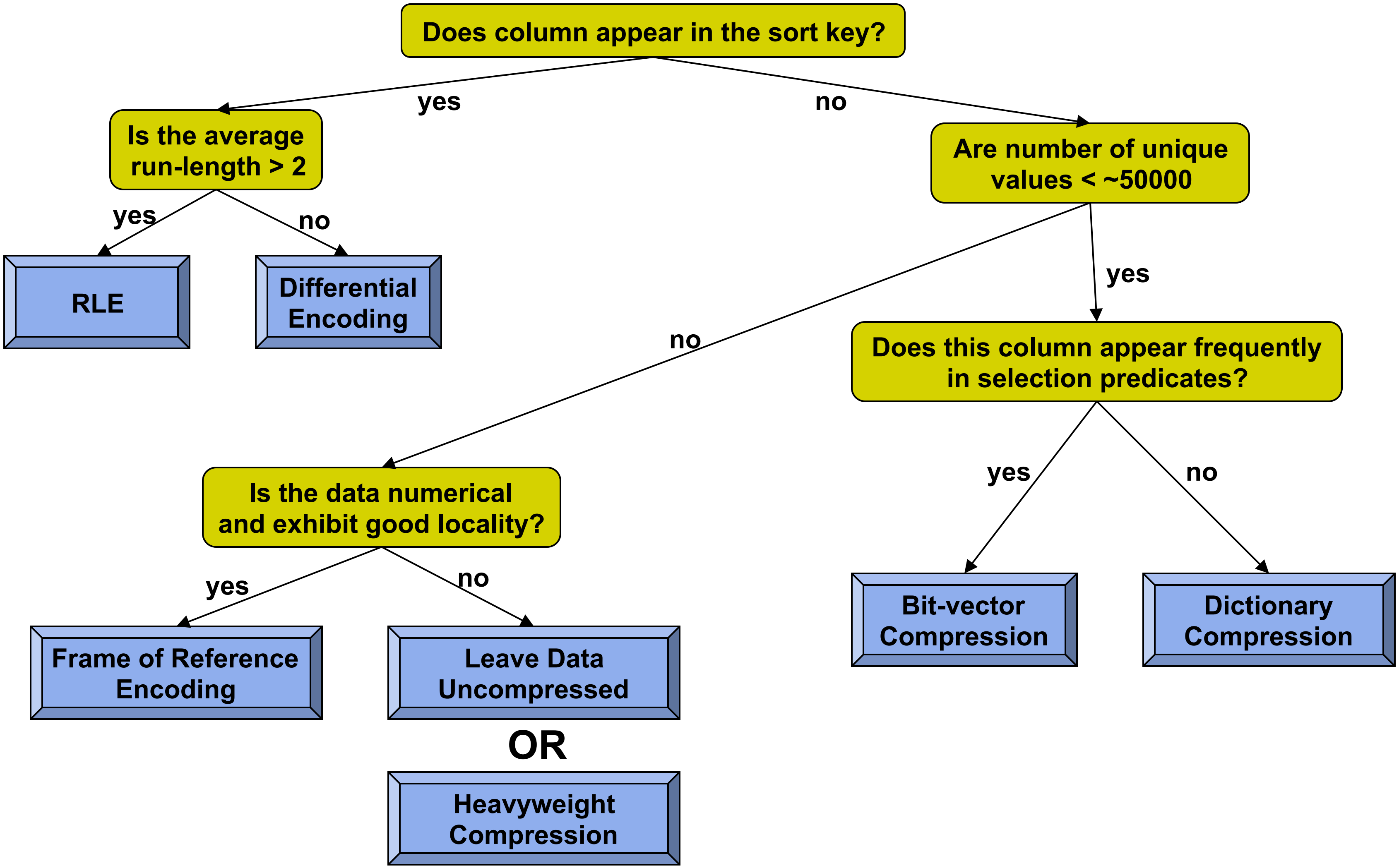
Differential Encoding

- Encodes values as b bit offset from previous value
- Special escape code (just like frame of reference encoding) indicates a difference larger than can be stored in b bits
  - After escape code, original (uncompressed) value is written
- Performs well on columns containing increasing/decreasing sequences
  - inverted lists
  - timestamps
  - object IDs
  - sorted / clustered columns

"Improved Word-Aligned Binary Compression for Text Indexing"
Ahn, Moffat, TKDE' 06



What Compression Scheme To Use?



"Super-Scalar RAM-CPU Cache Compression"
Zukowski, Heman, Nes, Boncz, ICDE'06

Heavy-Weight Compression Schemes

Algorithm	Decompression Bandwidth
BZIP	10 MB/s
ZLIB	80 MB/s
LZO	300 MB/s

- Modern disk arrays can achieve > 1GB/s
- 1/3 CPU for decompression ➔ 3GB/s needed

➔ **Lightweight compression schemes are better**

➔ **Even better: operate directly on compressed data**

"Integrating Compression and Execution in Column-Oriented Database Systems" Abadi et. al, SIGMOD '06

Operating Directly on Compressed Data

- **I/O - CPU tradeoff is no longer a tradeoff**
- **Reduces memory–CPU bandwidth requirements**
- **Opens up possibility of operating on multiple records at once**

"Integrating Compression and Execution in Column-Oriented Database Systems" Abadi et. al, SIGMOD '06

Operating Directly on Compressed Data

Quarter

(Q1, 1, 300)
(Q2, 301, 6)
(Q3, 307, 500)
(Q4, 807, 600)

301-306

Product ID

1	2	3
…	…	…
1	0	0
0	0	1
0	1	0
1	0	0
1	0	0
0	0	1
0	1	0
1	0	0
0	0	1
0	1	0
0	0	1
…	…	…

Index Lookup + Offset jump

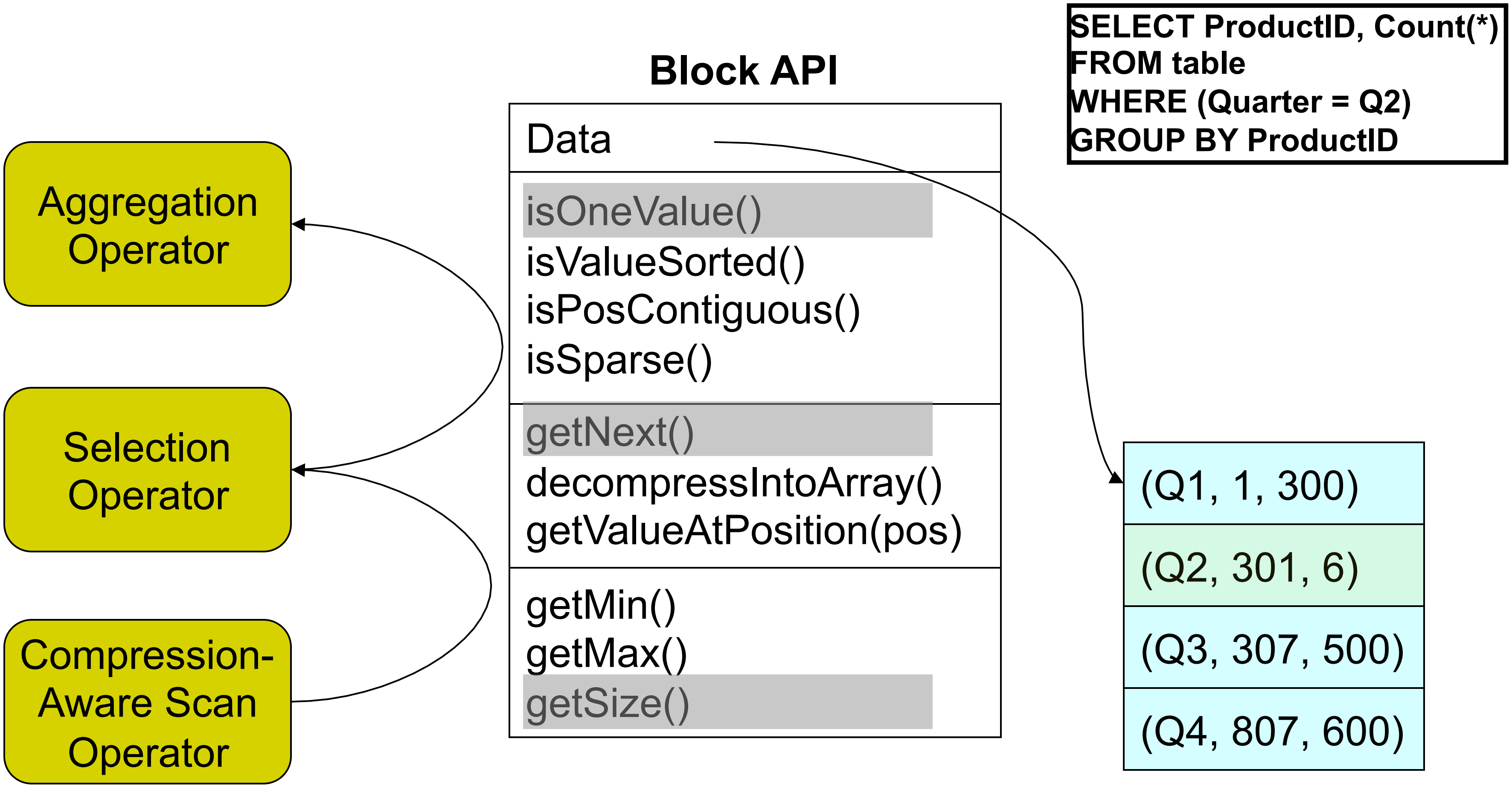
ProductID, COUNT(*))

(1, 3)
(2, 1)
(3, 2)

SELECT ProductID, Count(*)
FROM table
WHERE (Quarter = Q2)
GROUP BY ProductID

"Integrating Compression and Execution in Column-Oriented Database Systems" Abadi et. al, SIGMOD '06

Operating Directly on Compressed Data



Column-Oriented Database Systems

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Tuple Materialization and Column-Oriented Join Algorithms

"Materialization Strategies in a Column-Oriented DBMS" Abadi, Myers, DeWitt, and Madden. ICDE 2007.

"Self-organizing tuple reconstruction in column-stores", Idreos, Manegold, Kersten, SIGMOD' 09

"Column-Stores vs Row-Stores: How Different are They Really?" Abadi, Madden, and Hachem. SIGMOD 2008.

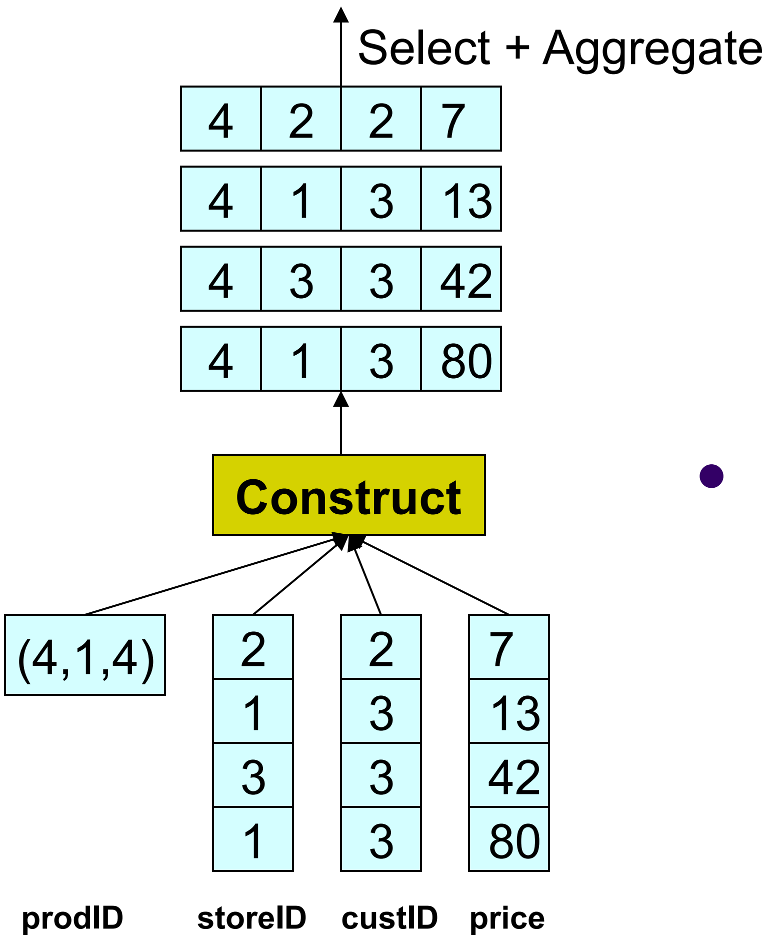
"Query Processing Techniques for Solid State Drives" Tsirogiannis, Harizopoulos Shah, Wiener, and Graefe. SIGMOD 2009.

"Cache-Conscious Radix-Decluster Projections", Manegold, Boncz, Nes, VLDB' 04

When should columns be projected?

- **Where should column projection operators be placed in a query plan?**
  - **Row-store:**
    - **Column projection involves removing unneeded columns from tuples**
    - **Generally done as early as possible**
  - **Column-store:**
    - **Operation is almost completely opposite from a row-store**
    - **Column projection involves reading needed columns from storage and extracting values for a listed set of tuples**
      - **This process is called "materialization"**
    - **Early materialization: project columns at beginning of query plan**
      - **Straightforward since there is a one-to-one mapping across columns**
    - **Late materialization: wait as long as possible for projecting columns**
      - **More complicated since selection and join operators on one column obfuscates mapping to other columns from same table**
    - **Most column-stores construct tuples and column projection time**
      - **Many database interfaces expect output in regular tuples (rows)**
      - **Rest of discussion will focus on this case**

When should tuples be constructed?

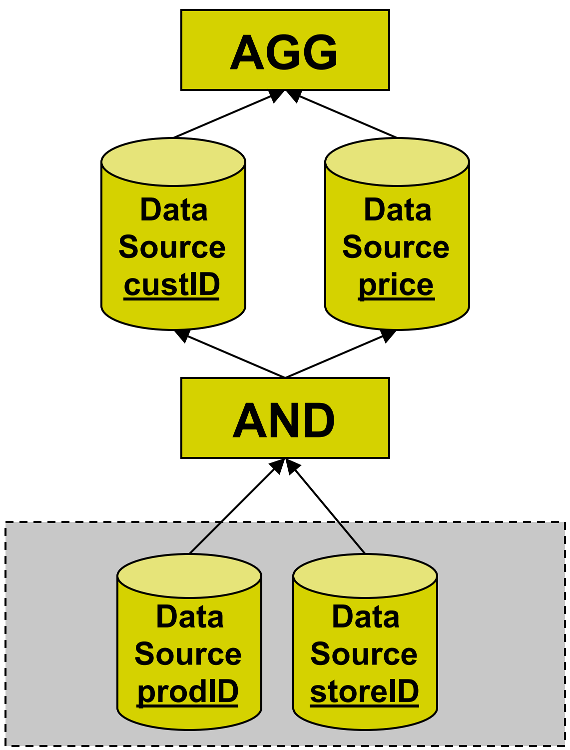


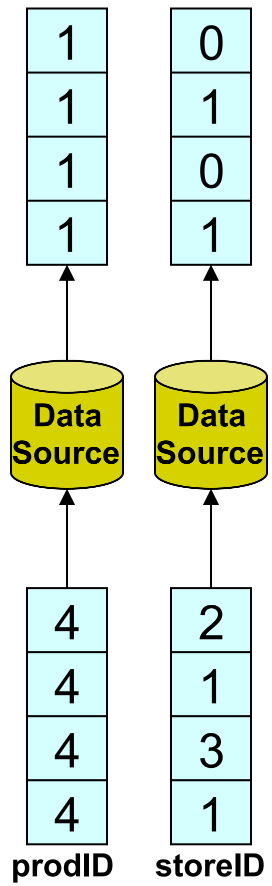
QUERY:

SELECT custID,SUM(price)
FROM table
WHERE (prodID = 4) AND
(storeID = 1) AND
GROUP BY custID

- **Solution 1: Create rows first (EM). But:**
  - **Need to construct ALL tuples**
  - **Need to decompress data**
  - **Poor memory bandwidth utilization**

Solution 2: Operate on columns



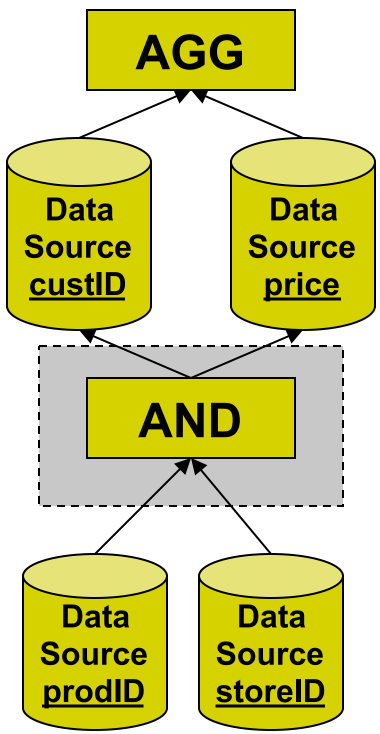


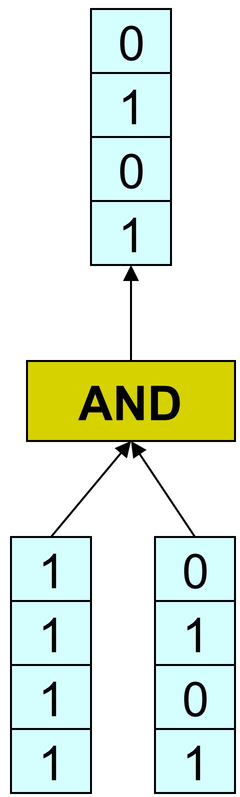
QUERY:

SELECT custID,SUM(price)
FROM table
WHERE (prodID = 4) AND
(storeID = 1) AND
GROUP BY custID

prodID	storeID	custID	price
4	2	2	7
4	1	3	13
4	3	3	42
4	1	3	80

Solution 2: Operate on columns





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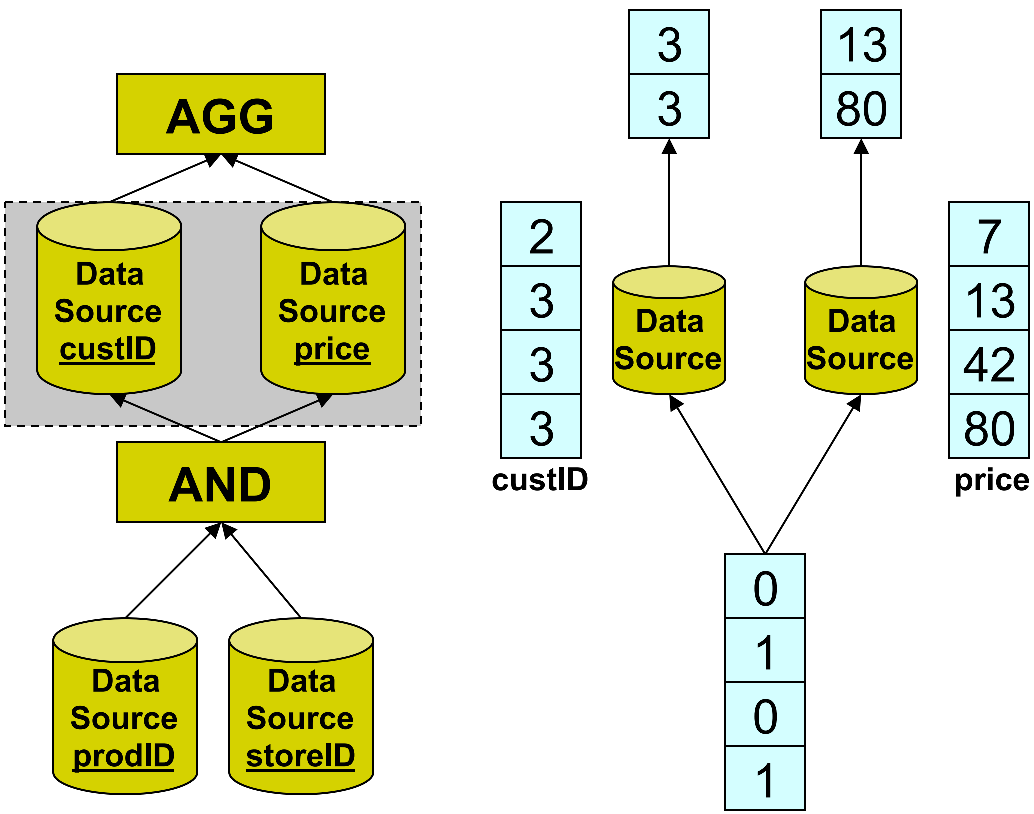

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prodID	**storeID**	**custID**	**price**

Solution 2: Operate on columns

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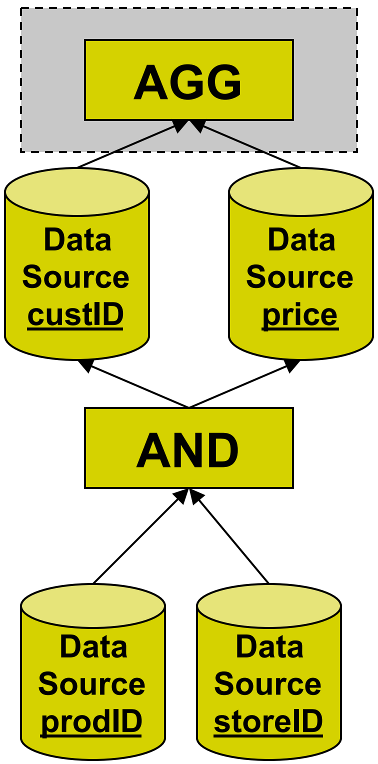
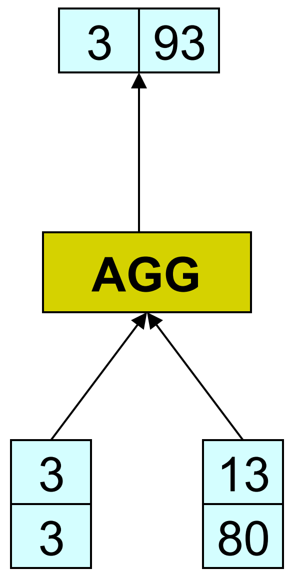
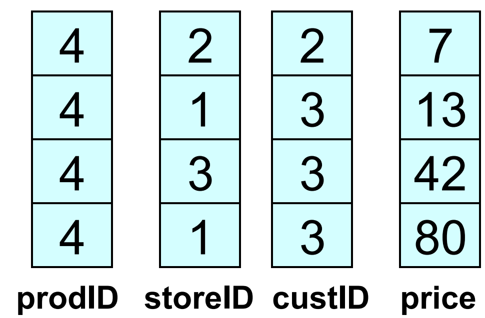
(storeID = 1) AND
GROUP BY custID

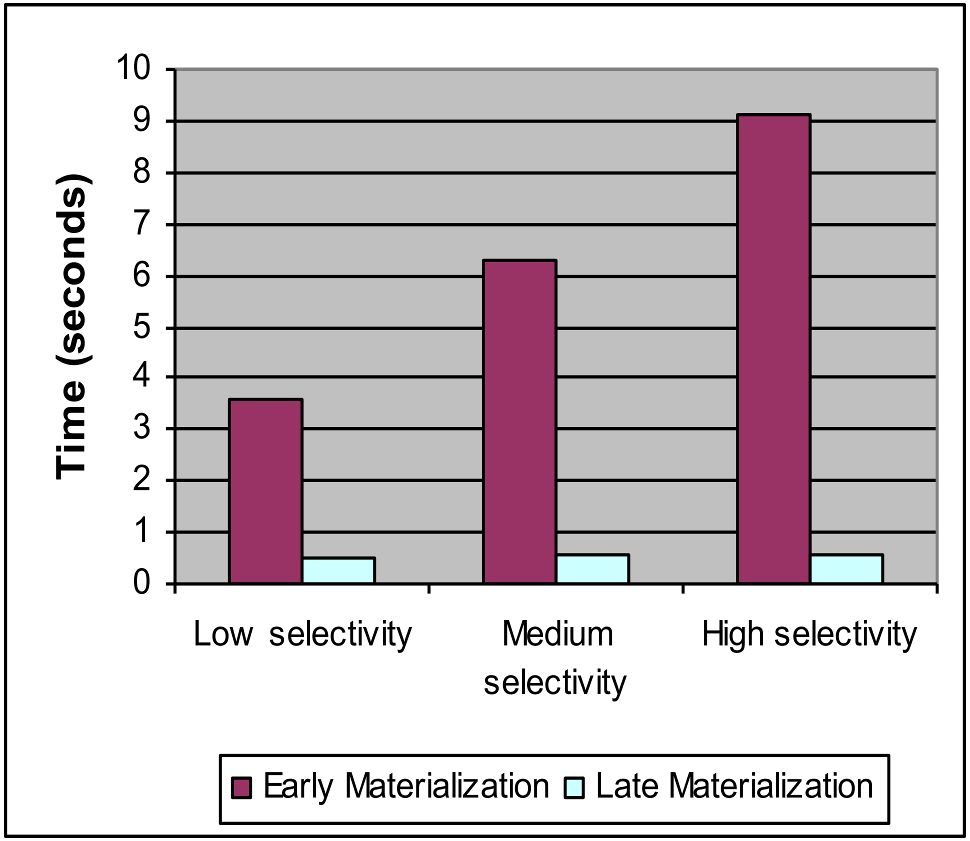






"Materialization Strategies in a Column-Oriented DBMS"
Abadi, Myers, DeWitt, and Madden. ICDE 2007.

For plans without joins, late materialization is a win



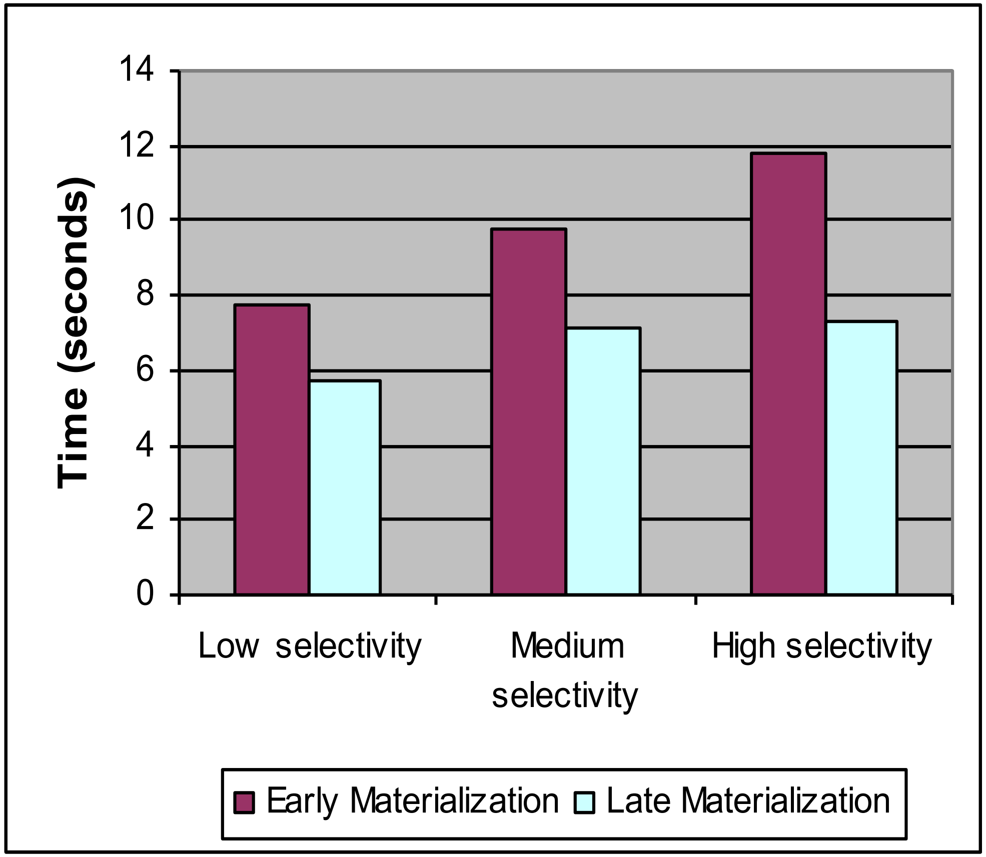
QUERY:

```
SELECT C1, SUM(C2)
FROM table
WHERE (C1 < CONST) AND
      (C2 < CONST)
GROUP BY C1
```

- **Ran on 2 compressed columns from TPC-H scale 10 data**

"Materialization Strategies in a Column-Oriented DBMS"
Abadi, Myers, DeWitt, and Madden. ICDE 2007.

Even on uncompressed data, late materialization is still a win



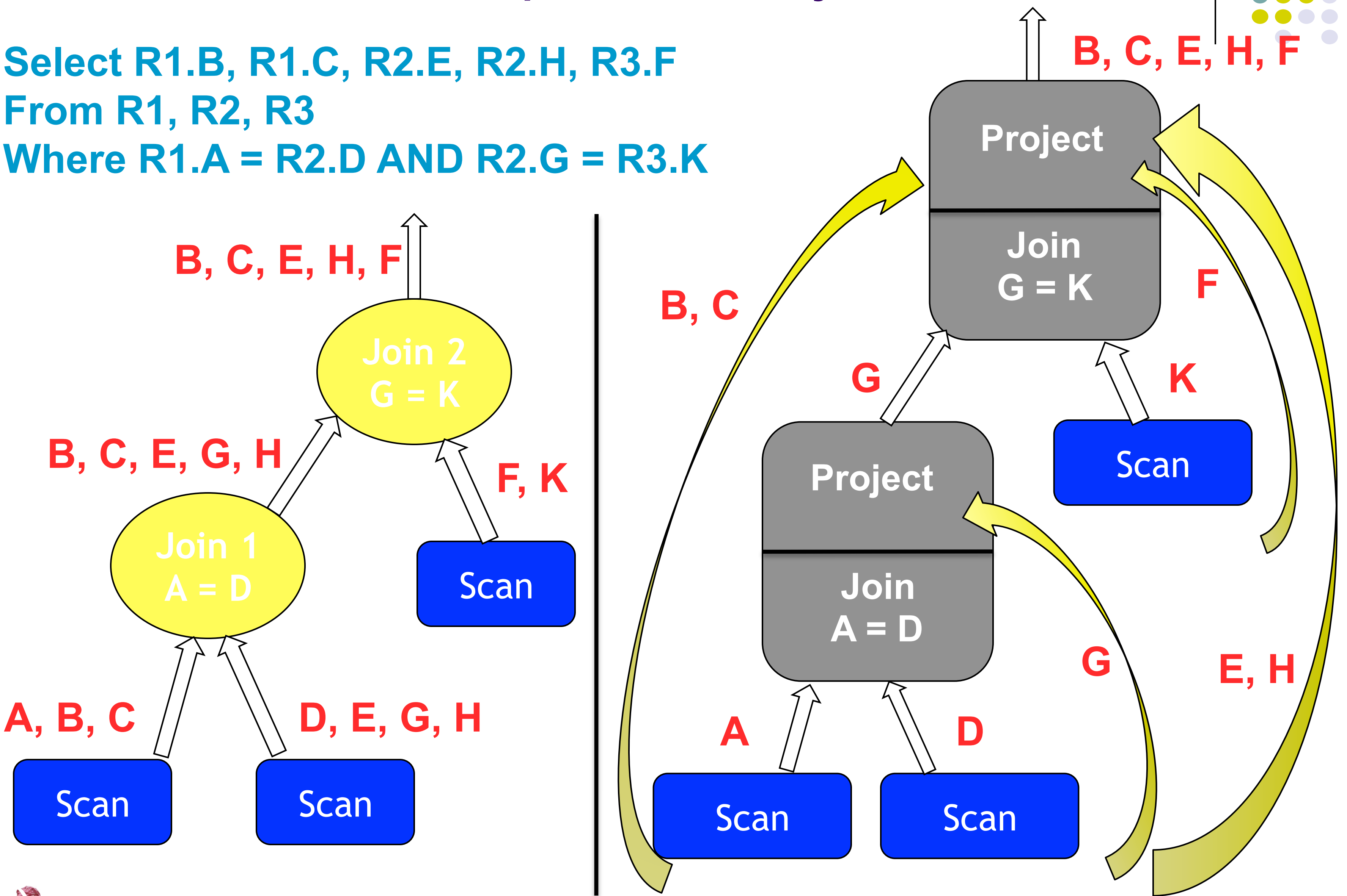
QUERY:

```
SELECT C1, SUM(C2)
FROM table
WHERE (C1 < CONST) AND
      (C2 < CONST)
GROUP BY C1
```

- **Materializing late still works best**

What about for plans with joins?

Select R1.B, R1.C, R2.E, R2.H, R3.F
From R1, R2, R3
Where R1.A = R2.D AND R2.G = R3.K



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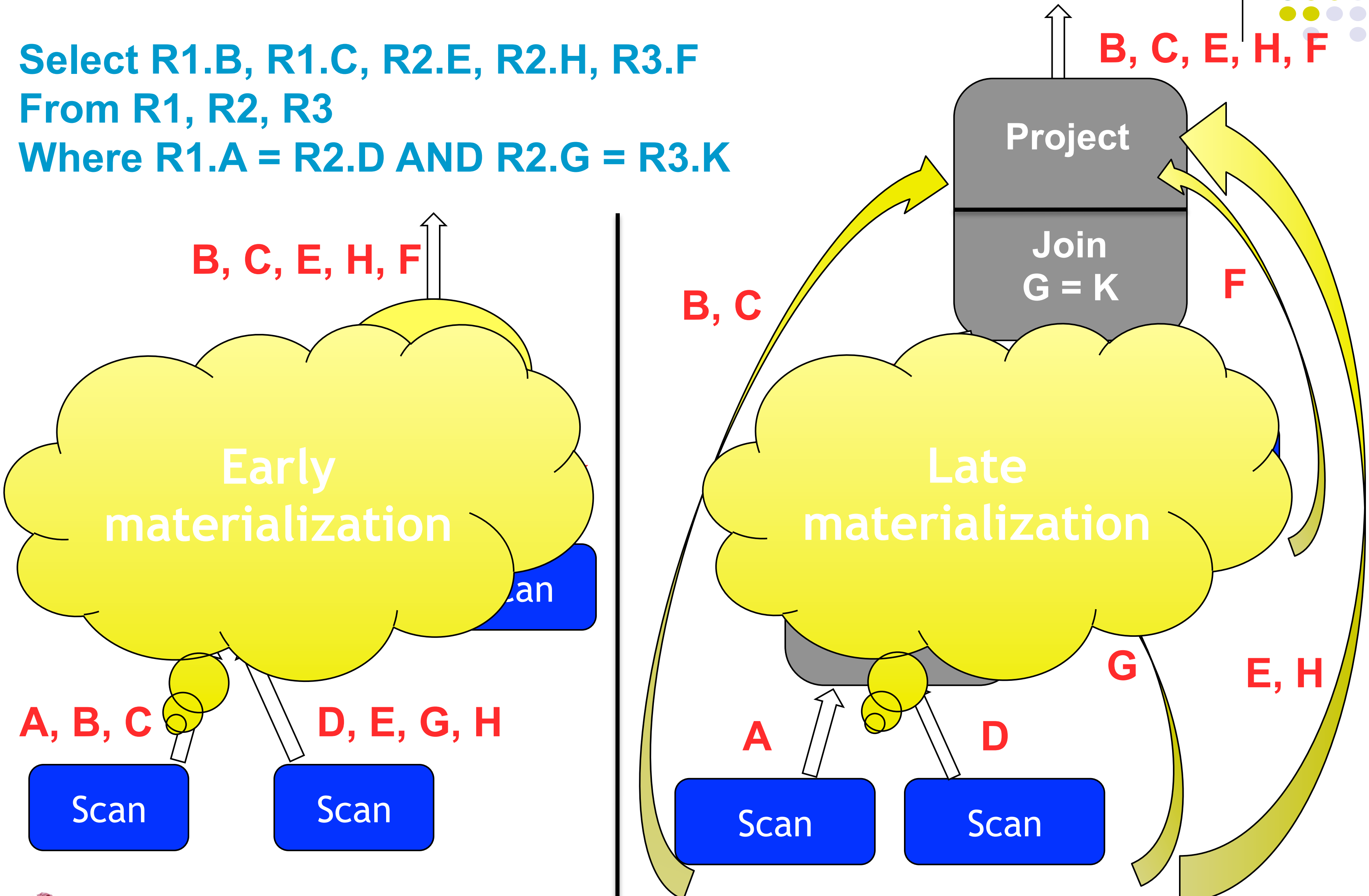
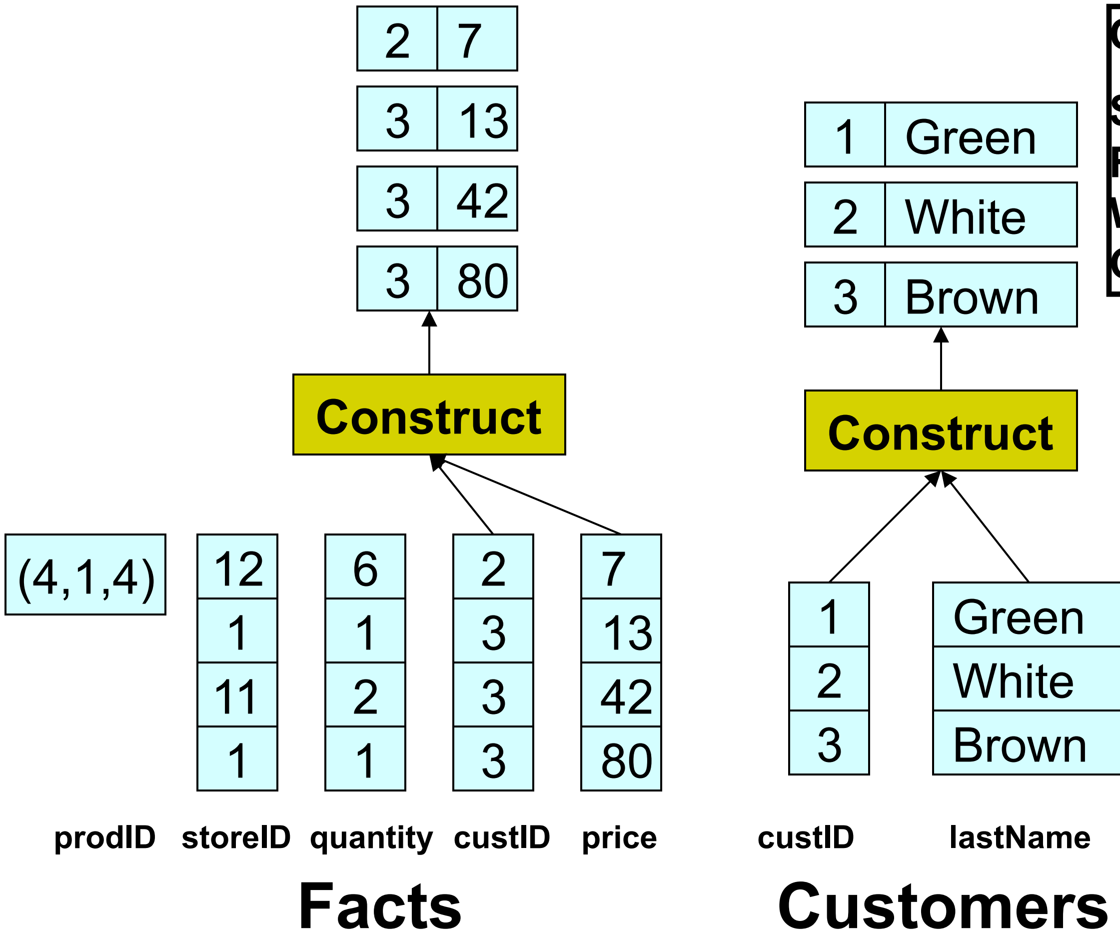


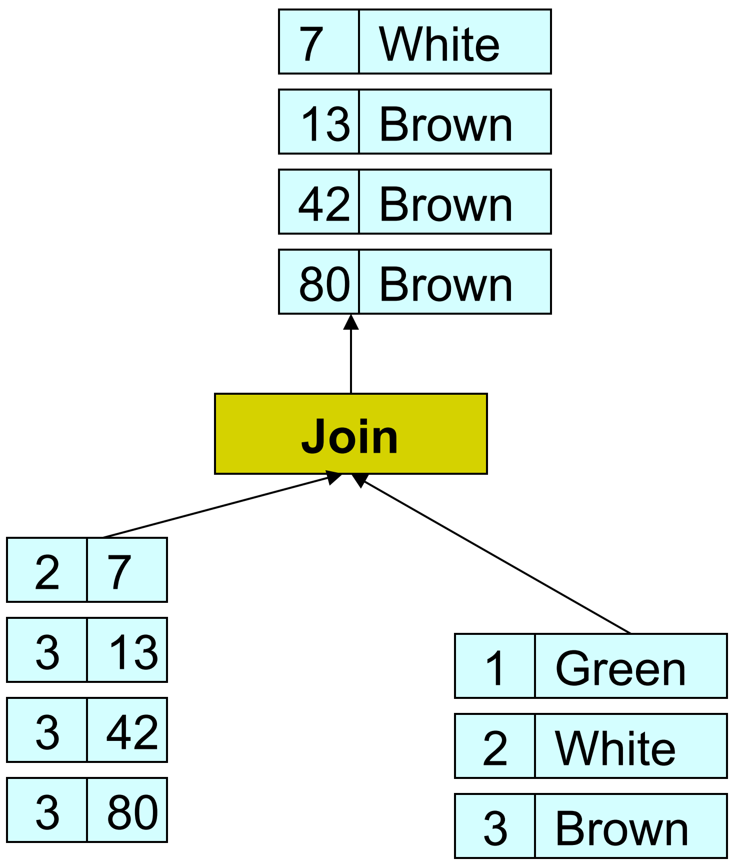
Early Materialization Example



QUERY:

SELECT C.lastName,SUM(F.price)
FROM facts AS F, customers AS C
WHERE F.custID = C.custID
GROUP BY C.lastName

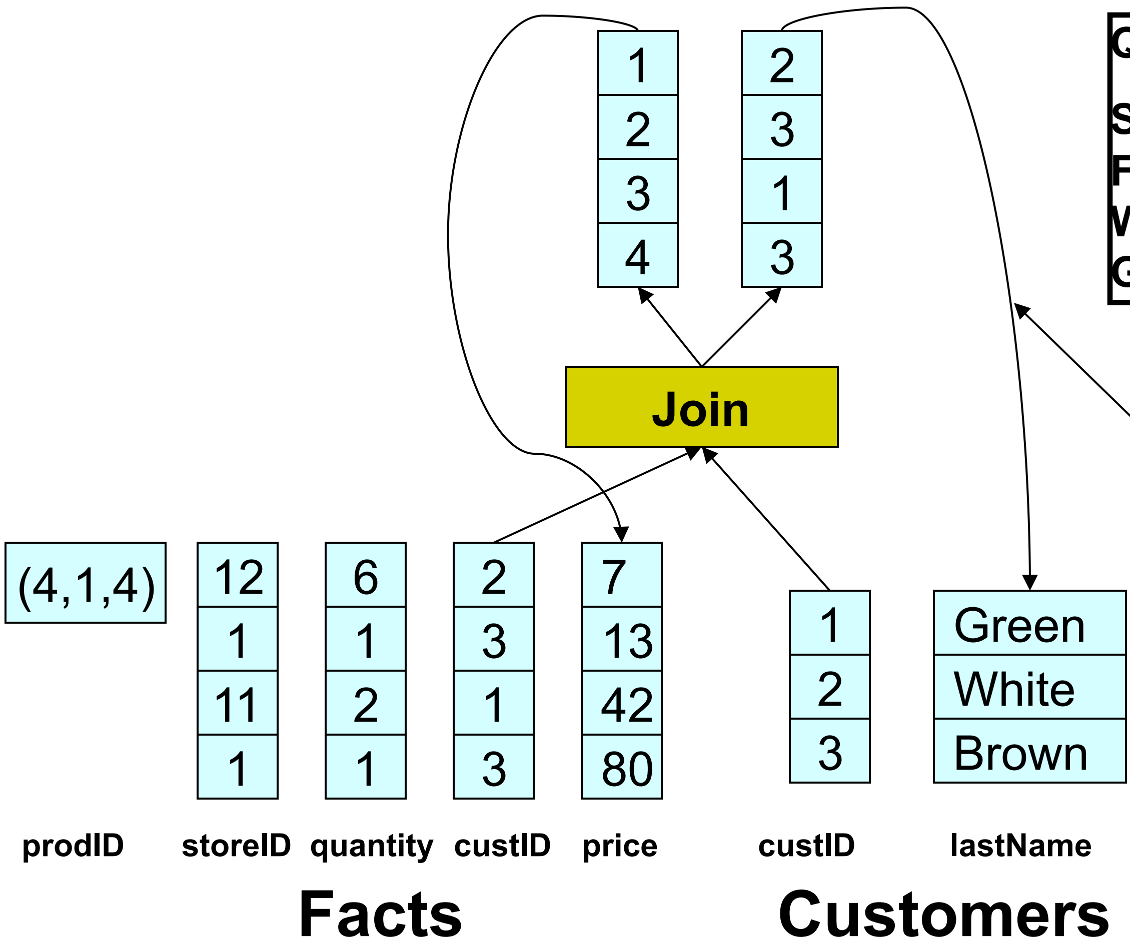
Early Materialization Example



QUERY:

SELECT C.lastName,SUM(F.price)
FROM facts AS F, customers AS C
WHERE F.custID = C.custID
GROUP BY C.lastName

Late Materialization Example



QUERY:

SELECT C.lastName,SUM(F.price)
FROM facts AS F, customers AS C
WHERE F.custID = C.custID
GROUP BY C.lastName

Late materialized join causes out of order probing of projected columns from the inner relation

Late Materialized Join Performance

- Naïve LM join about 2X slower than EM join on typical queries (due to random I/O)
  - This number is very dependent on
    - Amount of memory available
    - Number of projected attributes
    - Join cardinality
- But we can do better
  - Invisible Join
  - Jive/Flash Join
  - Radix cluster/decluster join

Invisible Join

"Column-Stores vs Row-Stores: How Different are They Really?" Abadi, Madden, and Hachem. SIGMOD 2008.

- Designed for typical joins when data is modeled using a star schema
  - One ("fact") table is joined with multiple dimension tables
- Typical query:

```
select c_nation, s_nation, d_year,
           sum(lo_revenue) as revenue
from customer, lineorder, supplier, date
where lo_custkey = c_custkey
   and lo_suppkey = s_suppkey
   and lo_orderdate = d_datekey
   and c_region = 'ASIA‘
   and s_region = 'ASIA‘
   and d_year >= 1992 and d_year <= 1997
group by c_nation, s_nation, d_year
order by d_year asc, revenue desc;
```

Invisible Join

"Column-Stores vs Row-Stores: How Different are They Really?" Abadi, Madden, and Hachem. SIGMOD 2008.

Apply "region = 'Asia'" On Customer Table

custkey	region	nation	…
1	ASIA	CHINA	…
2	ASIA	INDIA	…
3	ASIA	INDIA	…
4	EUROPE	FRANCE	…

→ **Hash Table (or bit-map) Containing Keys 1, 2 and 3**

Apply "region = 'Asia'" On Supplier Table

suppkey	region	nation	…
1	ASIA	RUSSIA	…
2	EUROPE	SPAIN	…
3	ASIA	JAPAN	…

→ **Hash Table (or bit-map) Containing Keys 1, 3**

Apply "year in [1992,1997]" On Date Table

dateid	year	…
01011997	1997	…
01021997	1997	…
01031997	1997	…

→ **Hash Table Containing Keys 01011997, 01021997, and 01031997**

Original Fact Table

orderkey	custkey	suppkey	orderdate	revenue
1	3	1	01011997	43256
2	3	2	01011997	33333
3	4	3	01021997	12121
4	1	1	01021997	23233
5	4	2	01021997	45456
6	1	2	01031997	43251
7	3	2	01031997	34235

"Column-Stores vs Row-Stores: How Different are They Really?" Abadi et. al. SIGMOD 2008.

	&		&		=	
1		1		1		1
1		0		1		0
0		1		1		0
1		1		1		1
0		0		1		0
1		0		1		0
1		0		1		0

Hash Table Containing Keys 1, 2 and 3

+

custkey	→	
3		1
3		1
4		0
1		1
4		0
1		1
3		1

Hash Table Containing Keys 1 and 3

+

suppkey	→	
1		1
2		0
3		1
1		1
2		0
2		0
2		0

Hash Table Containing Keys 01011997, 01021997, and 01031997

+

orderdate	→	
01011997		1
01011997		1
01021997		1
01021997		1
01021997		1
01031997		1
01031997		1

custkey
3
3
4
1
4
1
3

+

1
0
0
1
0
0
0

→

3
1

+

CHINA
INDIA
INDIA
FRANCE

=

INDIA
CHINA

suppkey
1
2
3
1
2
2
2

+

1
0
0
1
0
0
0

→

1
1

+

RUSSIA
SPAIN
JAPAN

=

RUSSIA
RUSSIA

orderdate
01011997
01011997
01021997
01021997
01021997
01031997
01031997

+

1
0
0
1
0
0
0

→

01011997
01021997

JOIN

01011997	1997
01021997	1997
01031997	1997

=

1997
1997

Invisible Join

"Column-Stores vs Row-Stores: How Different are They Really?" Abadi, Madden, and Hachem. SIGMOD 2008.

Apply "region = 'Asia' " On Customer Table

custkey	region	nation	…
1	ASIA	CHINA	…
2	ASIA	INDIA	…
3	ASIA	INDIA	…
4	EUROPE	FRANCE	…

→ ~~Hash Table (or bit-map) Containing Keys 1, 2 and 3~~

Range [1-3]
(between-predicate rewriting)

Apply "region = 'Asia' " On Supplier Table

suppkey	region	nation	…
1	ASIA	RUSSIA	…
2	EUROPE	SPAIN	…
3	ASIA	JAPAN	…

→ **Hash Table (or bit-map) Containing Keys 1, 3**

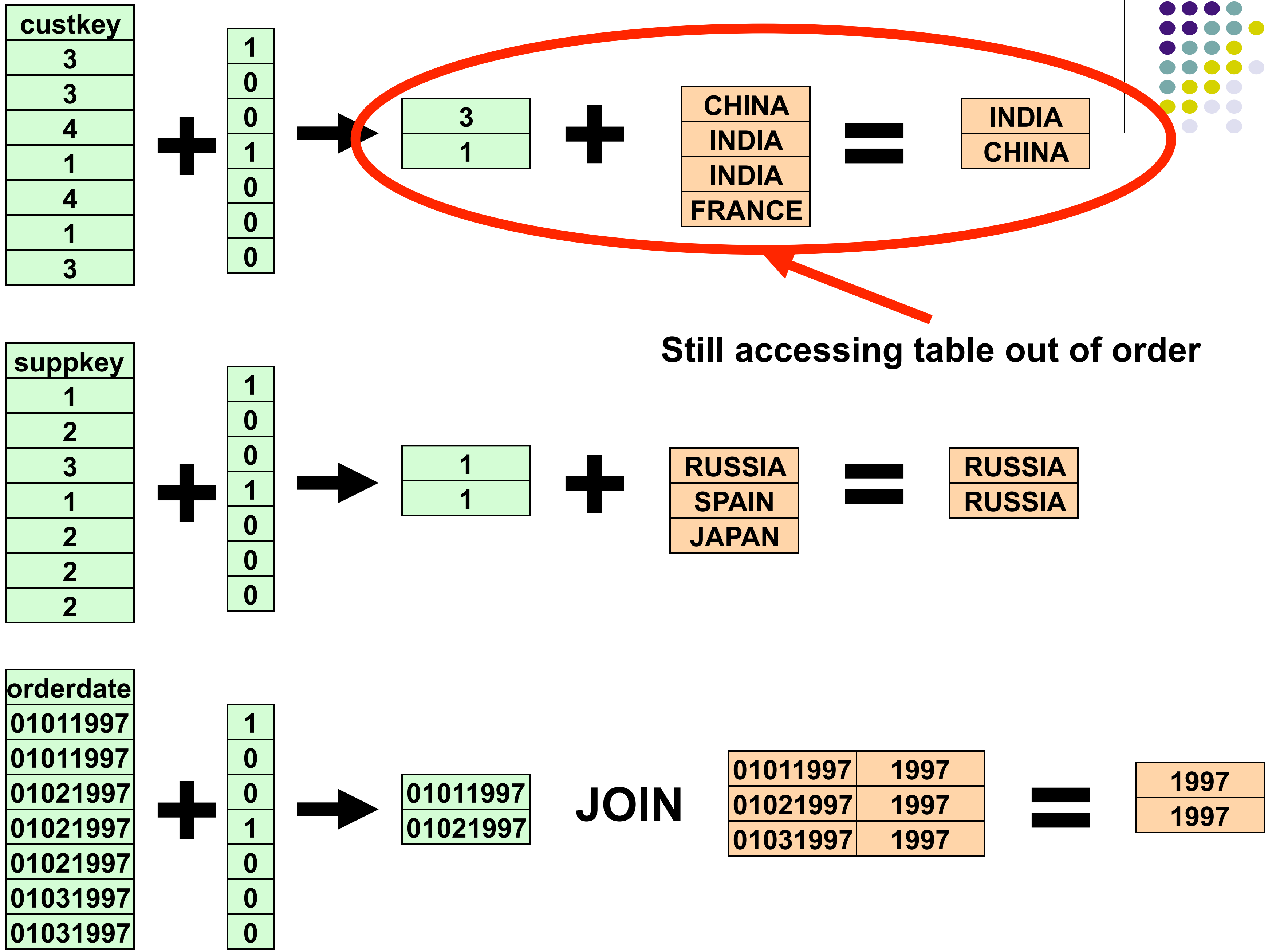
Apply "year in [1992,1997]" On Date Table

dateid	year	…
01011997	1997	…
01021997	1997	…
01031997	1997	…

→ **Hash Table Containing Keys 01011997, 01021997, and 01031997**

Invisible Join

- **Bottom Line**
  - **Many data warehouses model data using star/snowflake schemes**
  - **Joins of one (fact) table with many dimension tables is common**
  - **Invisible join takes advantage of this by making sure that the table that can be accessed in position order is the fact table for each join**
  - **Position lists from the fact table are then intersected (in position order)**
  - **This reduces the amount of data that must be accessed out of order from the dimension tables**
  - **“Between-predicate rewriting” trick not relevant for this discussion**


custkey
3
3
4
1
4
1
3
1
0
0
1
0
0
0
3
1
CHINA
INDIA
INDIA
FRANCE
INDIA
CHINA
Still accessing table out of order
suppkey
1
2
3
1
2
2
2
1
0
0
1
0
0
0
1
1
RUSSIA
SPAIN
JAPAN
RUSSIA
RUSSIA
orderdate
01011997
01011997
01021997
01021997
01021997
01031997
01031997
1
0
0
1
0
0
0
01011997
01021997
JOIN
01011997 1997
01021997 1997
01031997 1997
1997
1997

Jive/Flash Join

3
1

+

CHINA
INDIA
INDIA
FRANCE

=

INDIA
CHINA

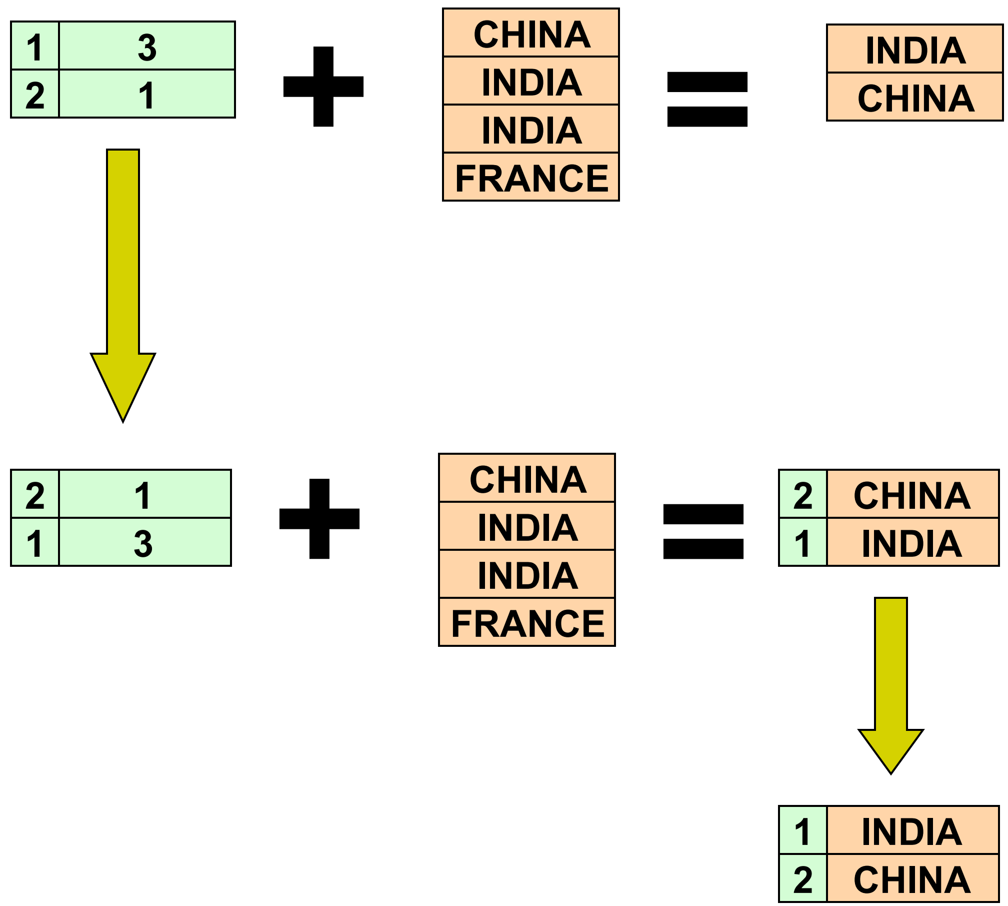
Still accessing table out of order

"Fast Joins using Join Indices". Li and Ross, VLDBJ 8:1-24, 1999.

"Query Processing Techniques for Solid State Drives". Tsirogiannis, Harizopoulos et. al. SIGMOD 2009.

Jive/Flash Join

1. Add column with dense ascending integers from 1
2. Sort new position list by second column
3. Probe projected column in order using new sorted position list, keeping first column from position list around
4. Sort new result by first column



Jive/Flash Join

- **Bottom Line**
  - **Instead of probing projected columns from inner table out of order:**
    - **Sort join index**
    - **Probe projected columns in order**
    - **Sort result using an added column**
  - **LM vs EM tradeoffs:**
    - **LM has the extra sorts (EM accesses all columns in order)**
    - **LM only has to fit join columns into memory (EM needs join columns and all projected columns)**
      - **Results in big memory and CPU savings (see part 3 for why there is CPU savings)**
    - **LM only has to materialize relevant columns**
    - **In many cases LM advantages outweigh disadvantages**
  - **LM would be a clear winner if not for those pesky sorts … can we do better?**

Radix Cluster/Decluster

- The full sort from the Jive join is actually overkill
  - We just want to access the storage blocks in order (we don't mind random access within a block)
  - So do a radix sort and stop early
  - By stopping early, data within each block is accessed out of order, but in the order specified in the original join index
    - Use this pseudo-order to accelerate the post-probe sort as well

•"Database Architecture Optimized for the New Bottleneck: Memory Access"
VLDB' 99
•"Generic Database Cost Models for Hierarchical Memory Systems", VLDB' 02
(all Manegold, Boncz, Kersten)

"Cache-Conscious Radix-Decluster Projections", Manegold, Boncz, Nes, VLDB' 04

Radix Cluster/Decluster

- Bottom line
  - Both sorts from the Jive join can be significantly reduced in overhead
  - Only been tested when there is sufficient memory for the entire join index to be stored three times
    - Technique is likely applicable to larger join indexes, but utility will go down a little
  - Only works if random access within a storage block
    - Don't want to use radix cluster/decluster if you have variable-width column values or compression schemes that can only be decompressed starting from the beginning of the block

LM vs EM joins

- Invisible, Jive, Flash, Cluster, Decluster techniques contain a bag of tricks to improve LM joins
- Research papers show that LM joins become 2X faster than EM joins (instead of 2X slower) for a wide array of query types

Tuple Construction Heuristics

- For queries with selective predicates, aggregations, or compressed data, use late materialization
- For joins:
  - Research papers:
    - Always use late materialization
  - Commercial systems:
    - Inner table to a join often materialized before join (reduces system complexity):
    - Some systems will use LM only if columns from inner table can fit entirely in memory

Outline

- Computational Efficiency of DB on modern hardware
  - how column-stores can help here
  - Keynote revisited: MonetDB & VectorWise in more depth
- CPU efficient column compression
  - vectorized decompression
- Conclusions
  - future work

Column-Oriented Database Systems

VLDB 2009 Tutorial

40 years of hardware evolution

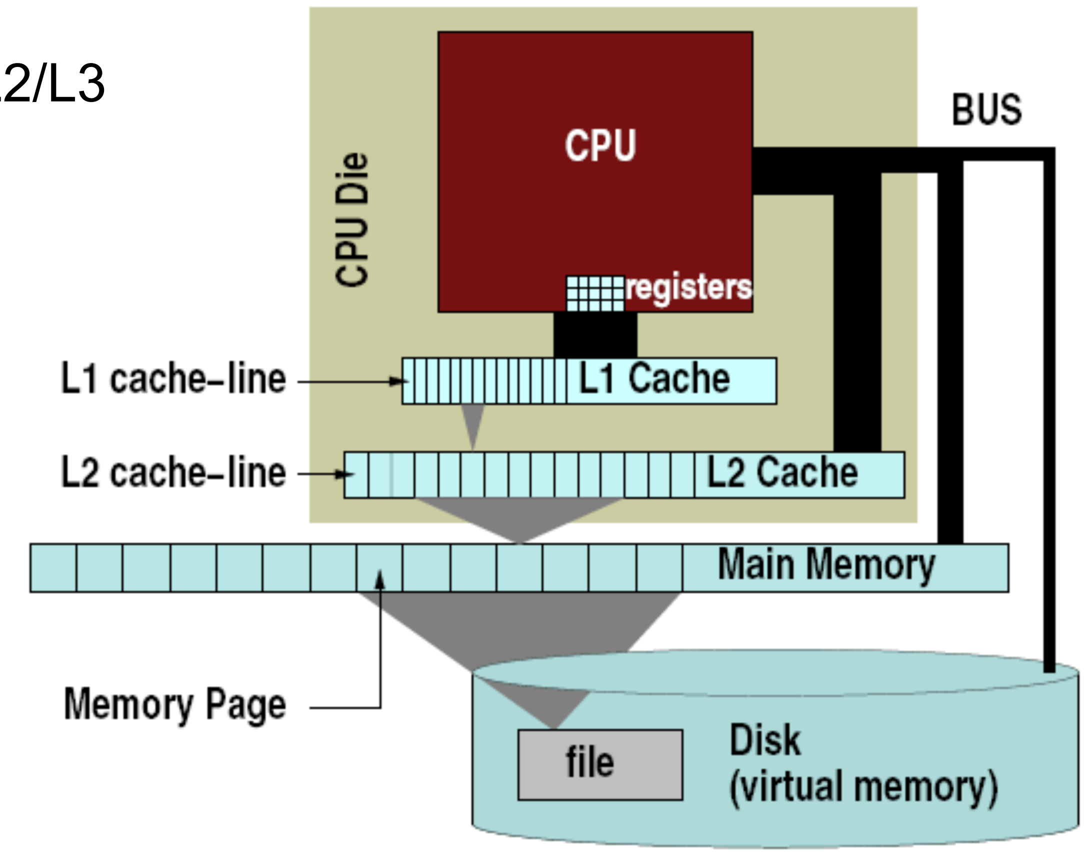
vs.

DBMS computational efficiency

CPU Architecture

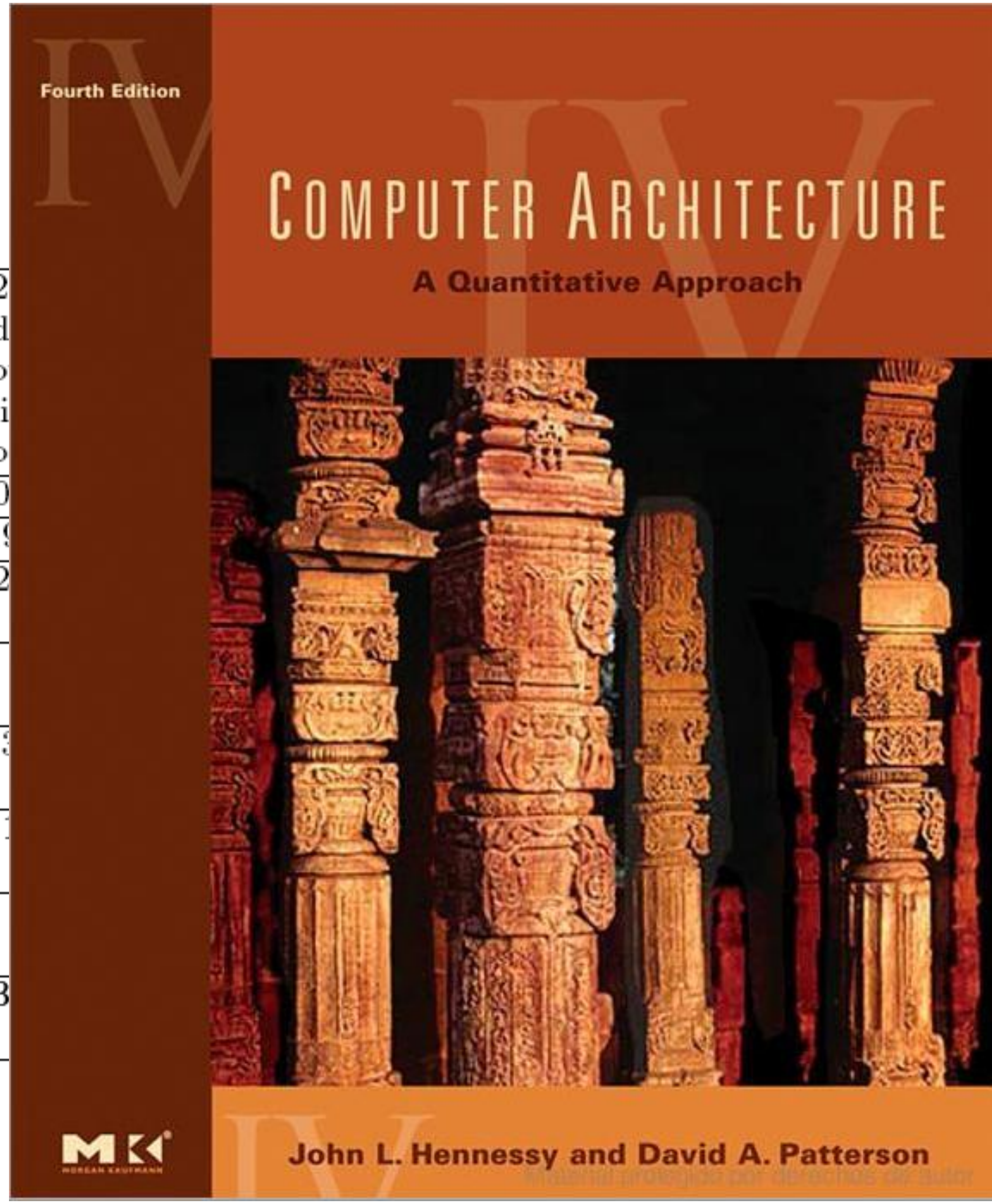
Elements:

- Storage
  - CPU caches L1/L2/L3
- Registers
- Execution Unit(s)
  - Pipelined
  - SIMD



CPU Metrics

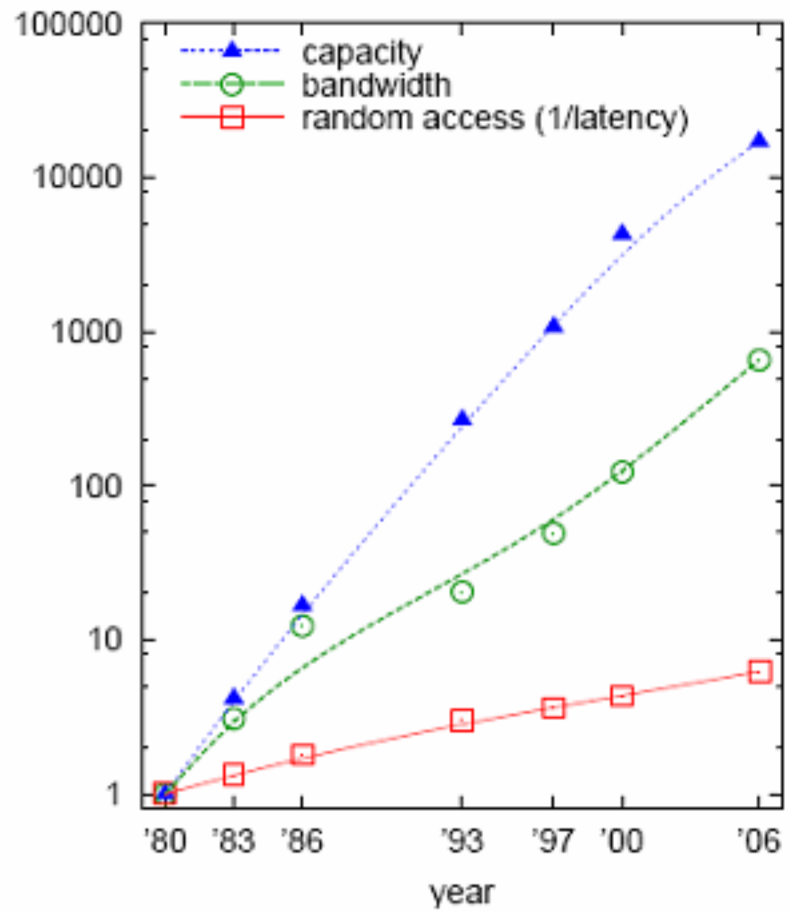
Processor	16-bit address/, bus, micro-coded	32 add b mi co	core
Product	80286	80	Duo
Year	1982	19	6
Transistors (thousands)	134	2	00
Latency (clocks)	6		
Bus width (bits)	16	3	
Clock rate (MHz)	12.5	1	3
Bandwidth (MIPS)	2		00
Latency (ns)	320	3	



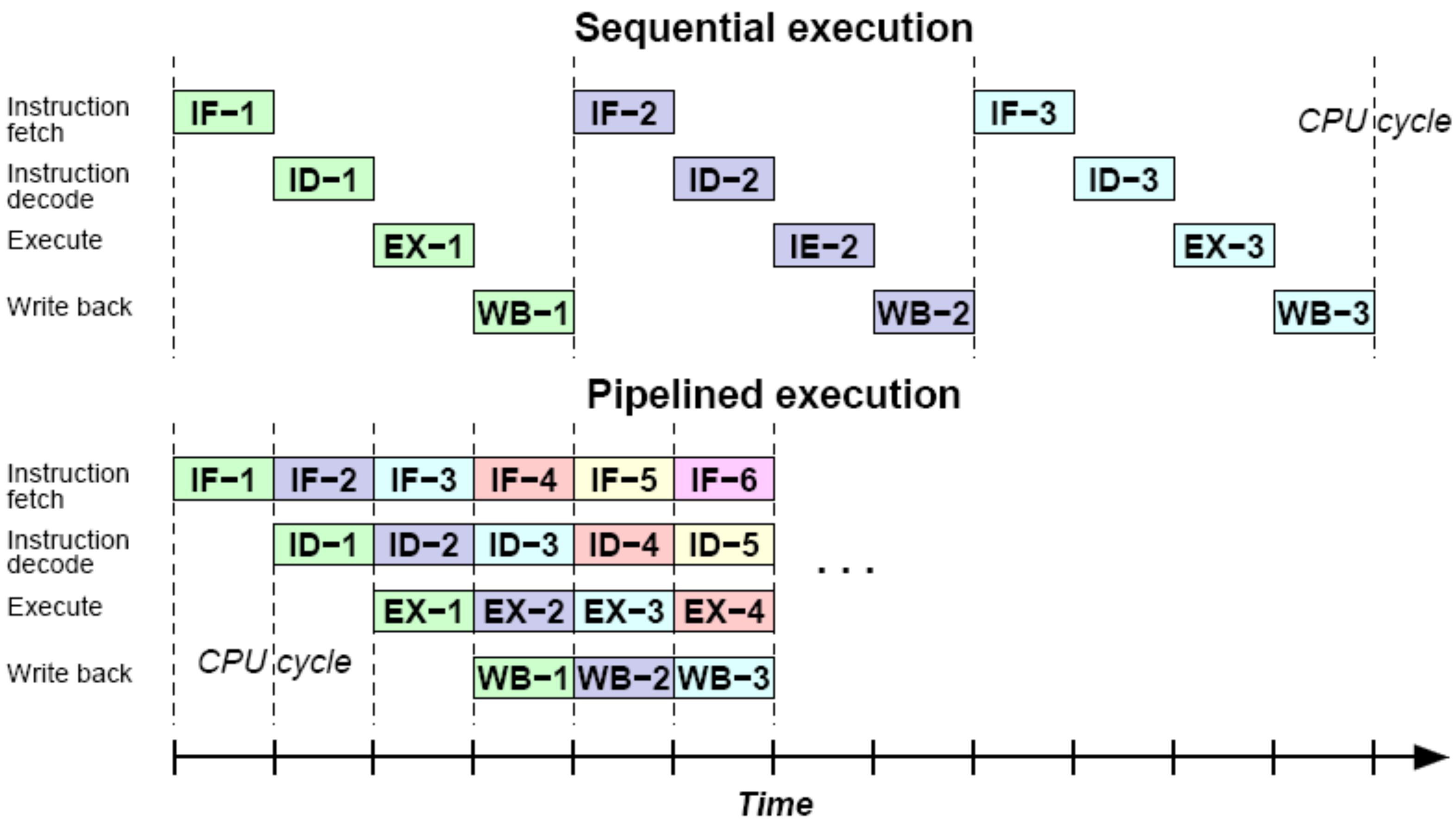
CPU Metrics

Processor	16-bit address/, bus, micro-coded	32-bit address/ bus, micro-coded	5-stage pipeline, on-chip I&D caches FPU	2-way super-scalar, 64-bit bus	Out-of-order, 3-way super-scalar	Out-of-order, super-pipelined, on-chip L2 cache	Multi-core
Product	80286	80386	80486	Pentium	PentiumPro	Pentium4	CoreDuo
Year	1982	1985	1989	1993	1997	2001	2006
Transistors (thousands)	134	275	1,200	3,100	5,500	42,000	151,600
Latency (clocks)	6	5	5	5	10	22	12
Bus width (bits)	16	32	32	64	64	64	64
Clock rate (MHz)	12.5	16	25	66	200	1500	2333
Bandwidth (MIPS)	2	6	25	132	600	4500	21000
Latency (ns)	320	313	200	76	50	15	5

DRAM Metrics



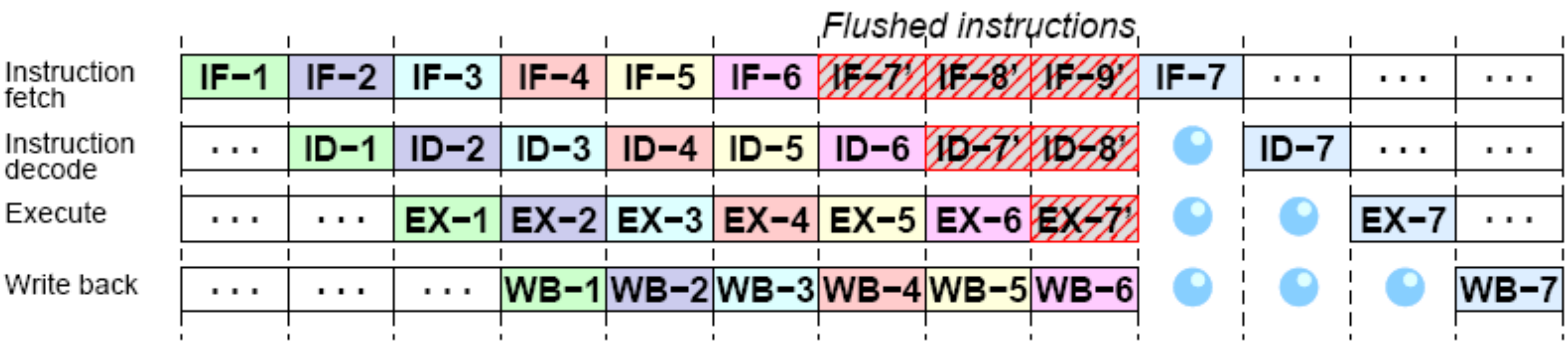
Super-Scalar Execution (pipelining)



Hazards

- Data hazards
  - Dependencies between instructions
  - L1 data cache misses
- Control Hazards
  - Branch mispredictions
  - Computed branches (late binding)
  - L1 instruction cache misses

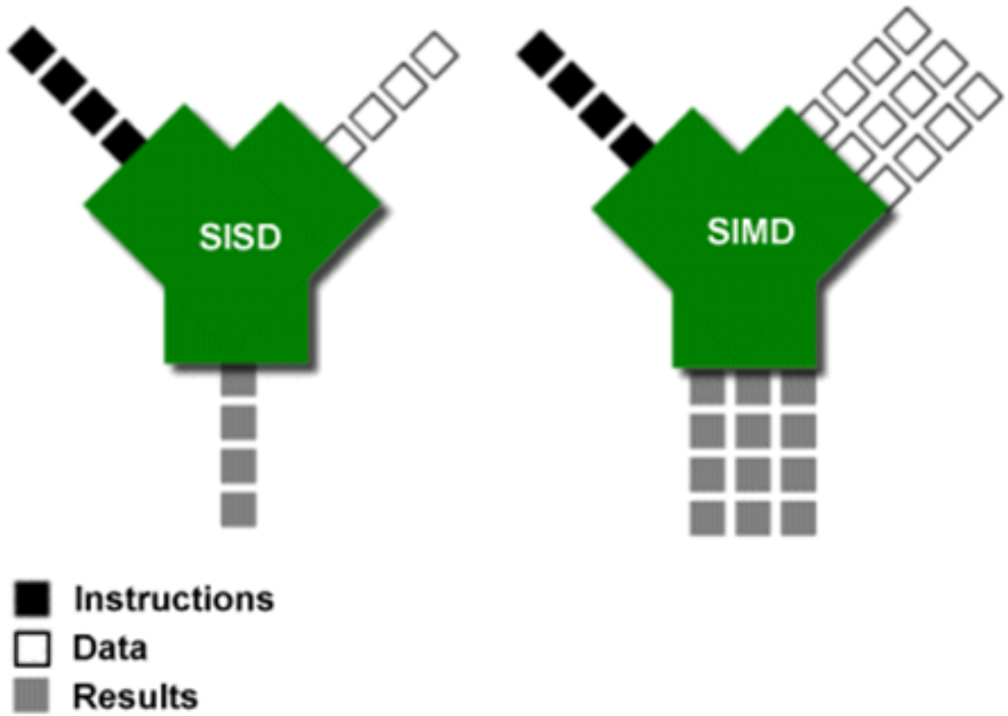
Result: bubbles in the pipeline



Out-of-order execution addresses data hazards

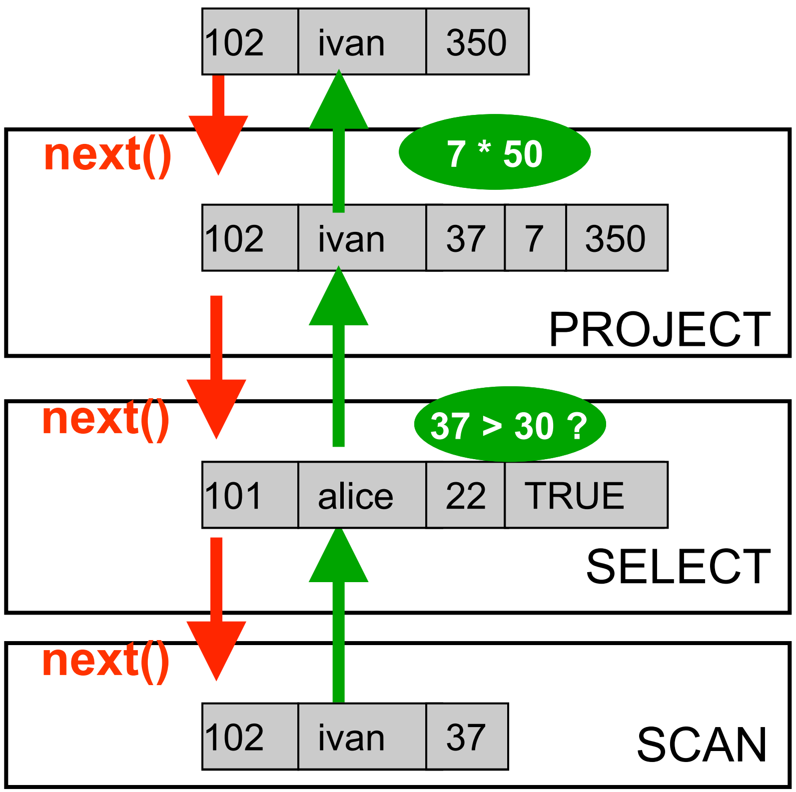
- control hazards typically more expensive

SIMD



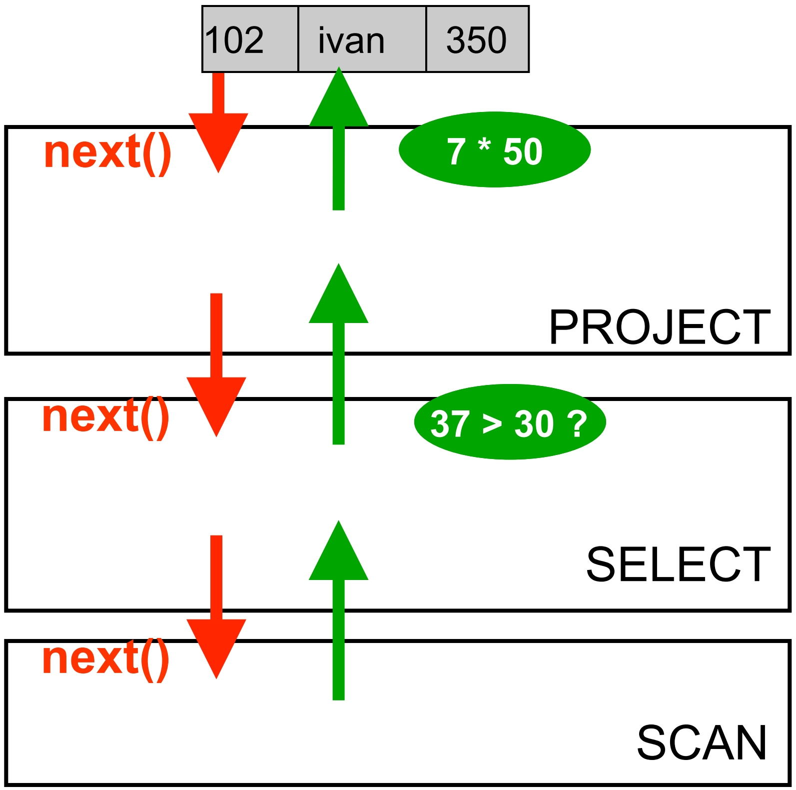
- Single Instruction Multiple Data
  - Same operation applied on a vector of values
  - MMX: 64 bits, SSE: 128bits, AVX: 256bits
  - SSE, e.g. multiply 8 short integers

A Look at the Query Pipeline



SELECT **id, name**
(age-30)*50 AS bonus
FROM **employee**
WHERE **age > 30**

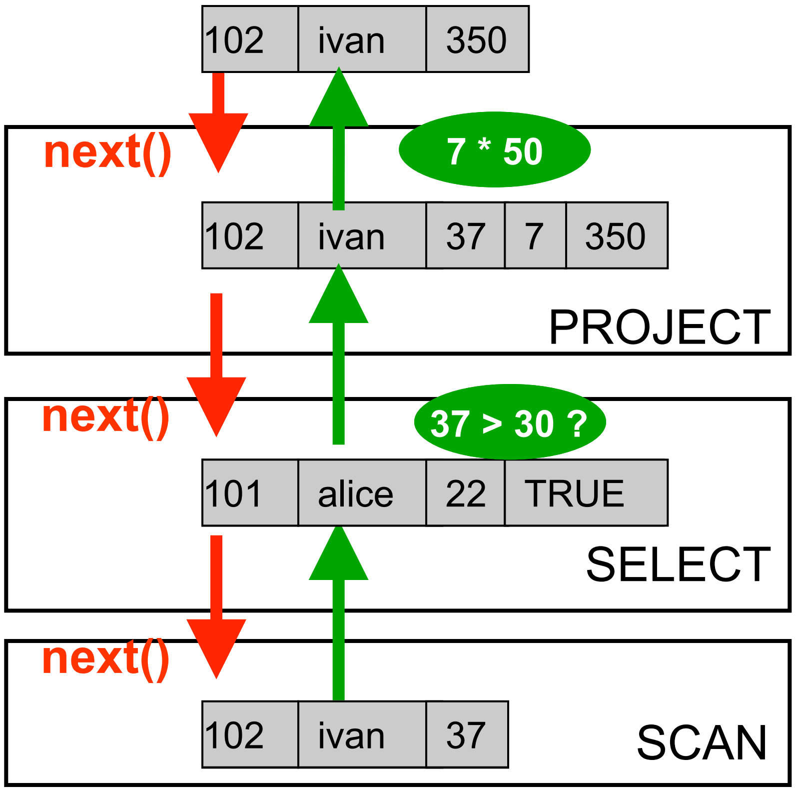
A Look at the Query Pipeline



Operators

Iterator interface
-open()
-next(): tuple
-close()

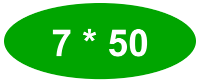
A Look at the Query Pipeline



Primitives

Provide computational functionality

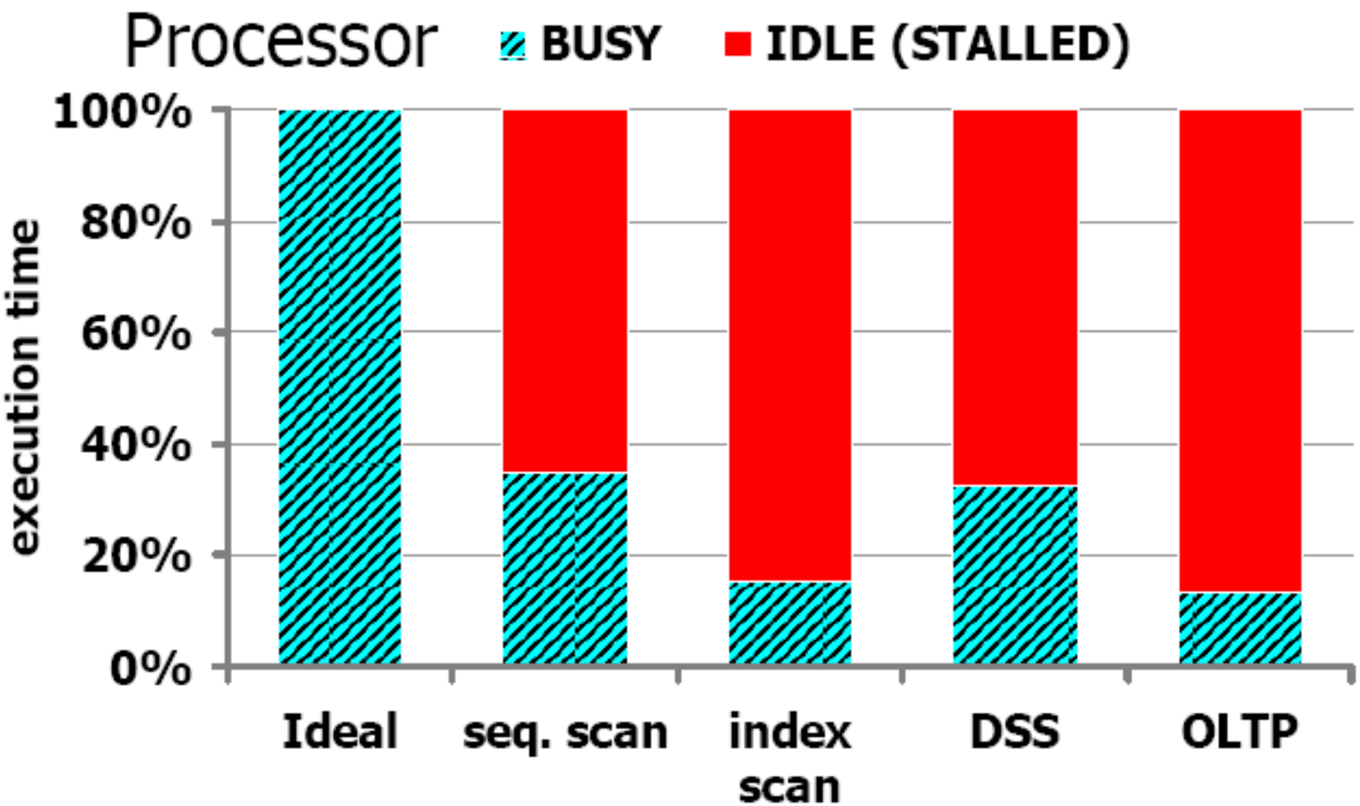
All arithmetic allowed in expressions,
e.g. Multiplication



`mult(int,int)` ➔ `int`

Database Architecture causes Hazards

- DB workload execution on a modern computer



"DBMSs On A Modern Processor: Where Does Time Go?"
Ailamaki, DeWitt, Hill, Wood, VLDB'99

DBMS Computational Efficiency

TPC-H 1GB, query 1

- selects 98% of fact table, computes net prices and aggregates all
- Results:
  - C program: ?
  - MySQL: 26.2s
  - DBMS "X": 28.1s

"MonetDB/X100: Hyper-Pipelining Query Execution " Boncz, Zukowski, Nes, CIDR' 05

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"MonetDB/X100: Hyper-Pipelining Query Execution" Boncz, Zukowski, Nes, CIDR'05

Column-Oriented Database Systems

VLDB 2009 Tutorial

MonetDB a column-store

- ~~"save disk I/O when scan-intensive queries need a few columns"~~
- "avoid an expression interpreter to improve computational efficiency"

RISC Database Algebra

people_id

(void)	(int)
0	101
1	102
2	104
3	105
4	108
5	109
6	112
7	113
8	114
9	115

people_name

(void)	(str)
0	Alice
1	Ivan
2	Peggy
3	Victor
4	Eve
5	Walter
6	Trudy
7	Bob
8	Zoe
9	Charlie

people_age

(void)	(int)
0	22
1	37
2	45
3	25
4	19
5	31
6	27
7	29
8	42
9	35

select(30,nil)

sel_age

(oid)	(int)
1	37
2	45
5	31
8	42
9	35

[−](,30)

tmp

(void)	(int)
0	7
1	15
2	1
3	12
4	5

```
SELECT   id, name, (age-30)*50 as bonus
FROM     people
WHERE    age > 30
```

RISC Database Algebra

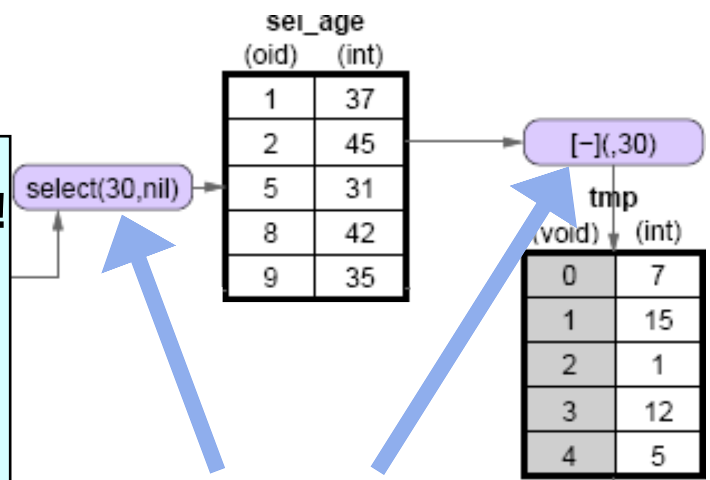
CPU happy? Give it "nice" code !

- few dependencies (control,data)
- CPU gets out-of-order execution
- compiler can e.g. generate SIMD

One loop for an entire column

- no per-tuple interpretation
- arrays: no record navigation
- better instruction cache locality

```
{
    for(i=0; i<n; i++)
        res[i] = col[i] - val;
}
```



Simple, hard-coded semantics in operators

RISC Database Algebra

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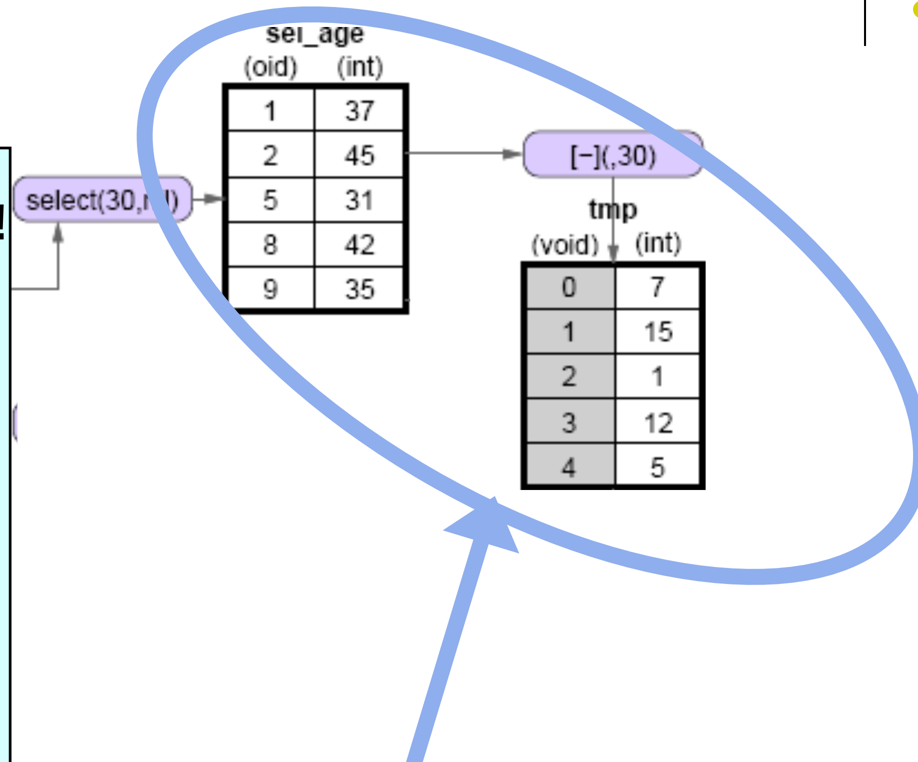


MATERIALIZED intermediate results

a column-store

- ~~“save disk I/O when scan-intensive queries need a few columns”~~
- ~~“avoid an expression interpreter to improve computational efficiency”~~

How?

- RISC query algebra: hard-coded semantics
  - Decompose complex expressions in multiple operations
- Operators only handle **simple arrays**
  - No code that handles slotted buffered record layout
- Relational algebra becomes **array manipulation language**
  - Often SIMD for free

  - Plus: use of *cache-conscious* algorithms for Sort/Aggr/Join

a Faustian pact

- You want efficiency
  - Simple hard-coded operators
- I take scalability
  - Result materialization

- C program: 0.2s
- MonetDB: 3.7s
- MySQL: 26.2s
- DBMS "X": 28.1s

Column-Oriented Database Systems

VLDB
2009
Tutorial

MonetDB as a research platform

SIGMOD 1985

A DECOMPOSITION STORAGE MODEL

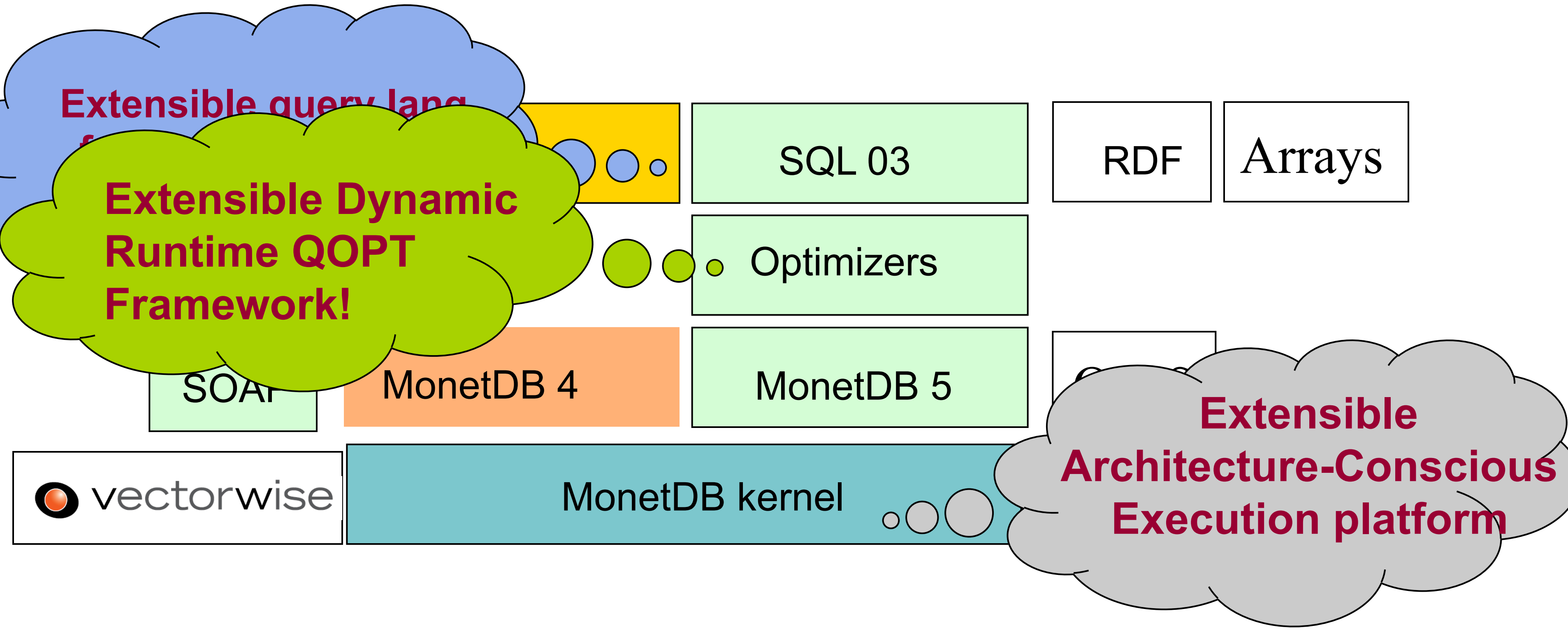
MonetDB BAT Algebra

MonetDB supports SQL, XML, ODMG, ..RDF

RDF support on C-STORE / SW-Store

- "MIL Primitives for Querying a Fragmented World", Boncz, Kersten, VLDBJ' 98
- "Flattening an Object Algebra to Provide Performance" Boncz, Wilschut, Kersten, ICDE' 98
- "MonetDB/XQuery: a fast XQuery processor powered by a relational engine" Boncz, Grust, vanKeulen, Rittinger, Teubner, SIGMOD' 06
- "SW-Store: a vertically partitioned DBMS for Semantic Web data management" Abadi, Marcus, Madden, Hollenbach, VLDBJ' 09

The MonetDB Software Stack



optimizer frontend backend

as a research platform

- Cache-Conscious Joins
  - Cost Models, Radix-cluster, Radix-decluster

•"Database Architecture Optimized for the New Bottleneck: Memory Access" VLDB'99
•"Generic Database Cost Models for Hierarchical Memory Systems", VLDB'02 (all Manegold, Boncz, Kersten)
•"Cache-Conscious Radix-Decluster Projections", Manegold, Boncz, Nes, VLDB'04

- MonetDB/XQuery:
  - structural joins exploiting positional column access

"MonetDB/XQuery: a fast XQuery processor powered by a relational engine" Boncz, Grust, vanKeulen, Rittinger, Teubner, SIGMOD'06

- Cracking:
  - on-the-fly automatic indexing without workload knowledge

"Database Cracking", CIDR'07
"Updating a cracked database ", SIGMOD'07
"Self-organizing tuple reconstruction in column-stores", SIGMOD'09 (all Idreos, Manegold, Kersten)

- Recycling:
  - using materialized intermediates

"An architecture for recycling intermediates in a column-store", Ivanova, Kersten, Nes, Goncalves, SIGMOD'09

- Run-time Query Optimization:
  - correlation-aware run-time optimization without cost model

"ROX: run-time optimization of XQueries", Abdelkader, Boncz, Manegold, vanKeulen, SIGMOD'09

Column-Oriented Database Systems

VLDB 2009 Tutorial

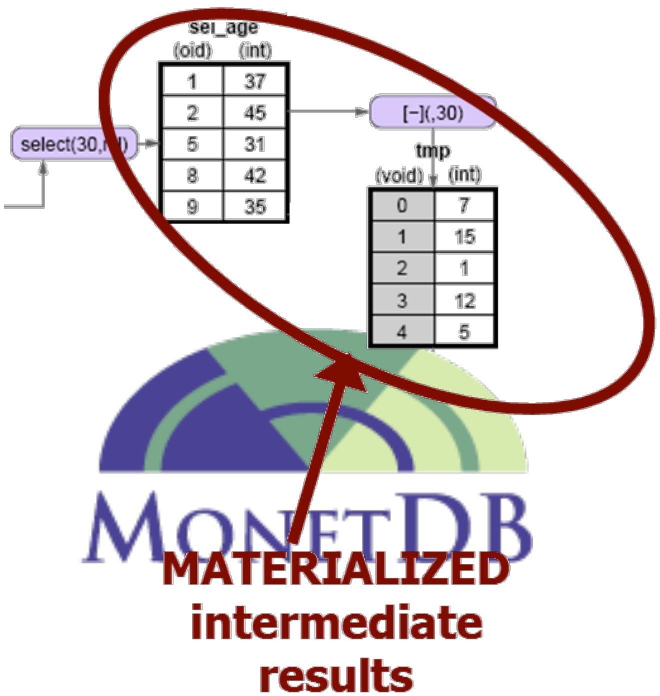
vectorwise

“MonetDB/X100”

vectorized query processing

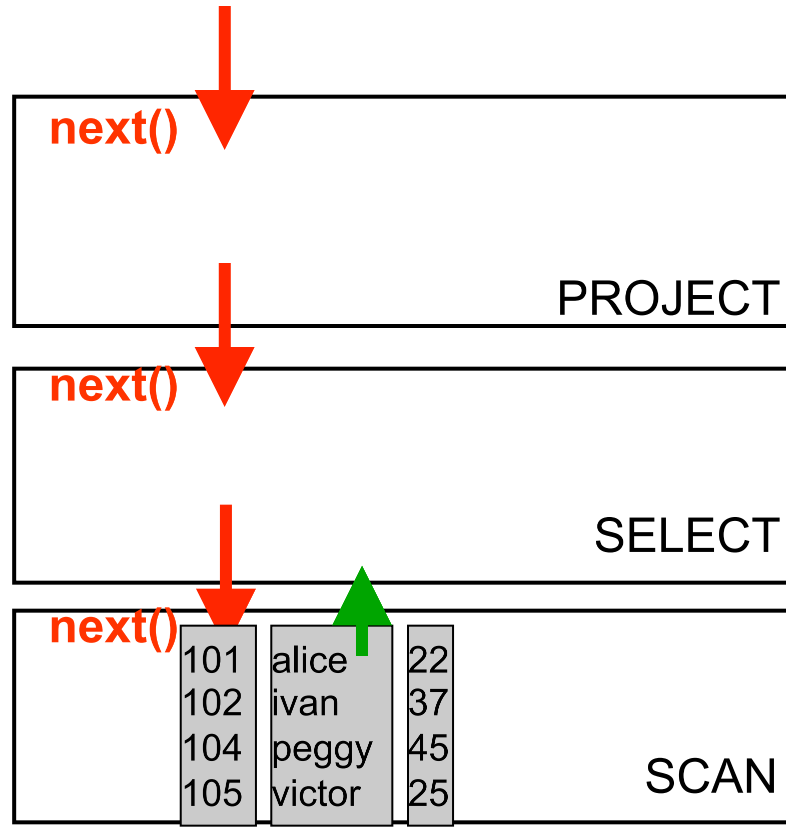
MonetDB spin-off: MonetDB/X100

Materialization vs Pipelining



"MonetDB/X100: Hyper-Pipelining Query Execution" Boncz, Zukowski, Nes, CIDR'05

vectorwise



"MonetDB/X100: Hyper-Pipelining Query Execution" Boncz, Zukowski, Nes, CIDR'05

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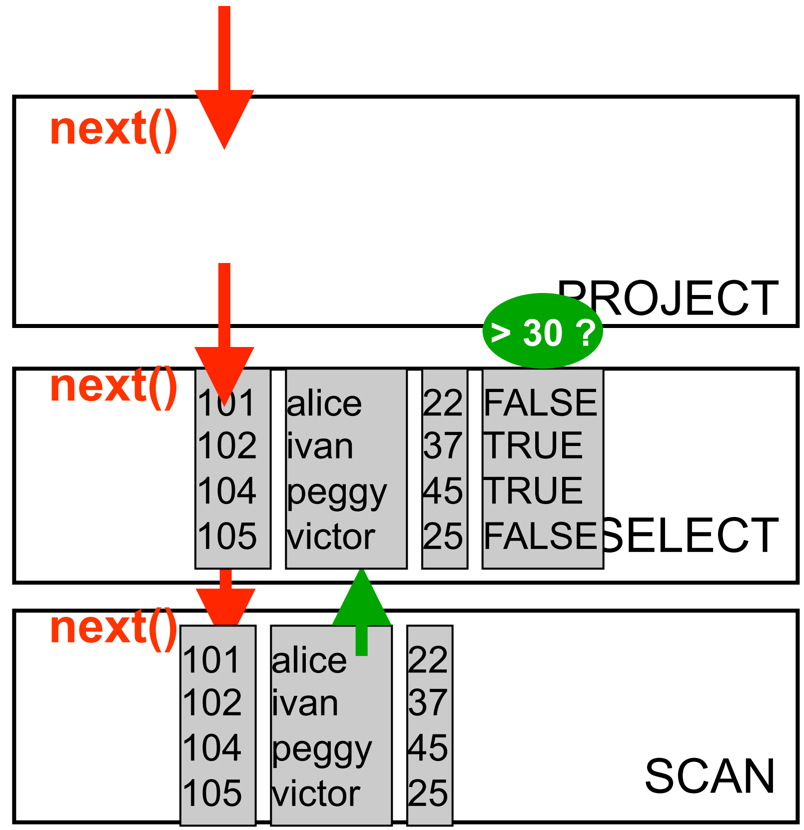


"MonetDB/X100: Hyper-Pipelining Query Execution" Boncz, Zukowski, Nes, CIDR'05

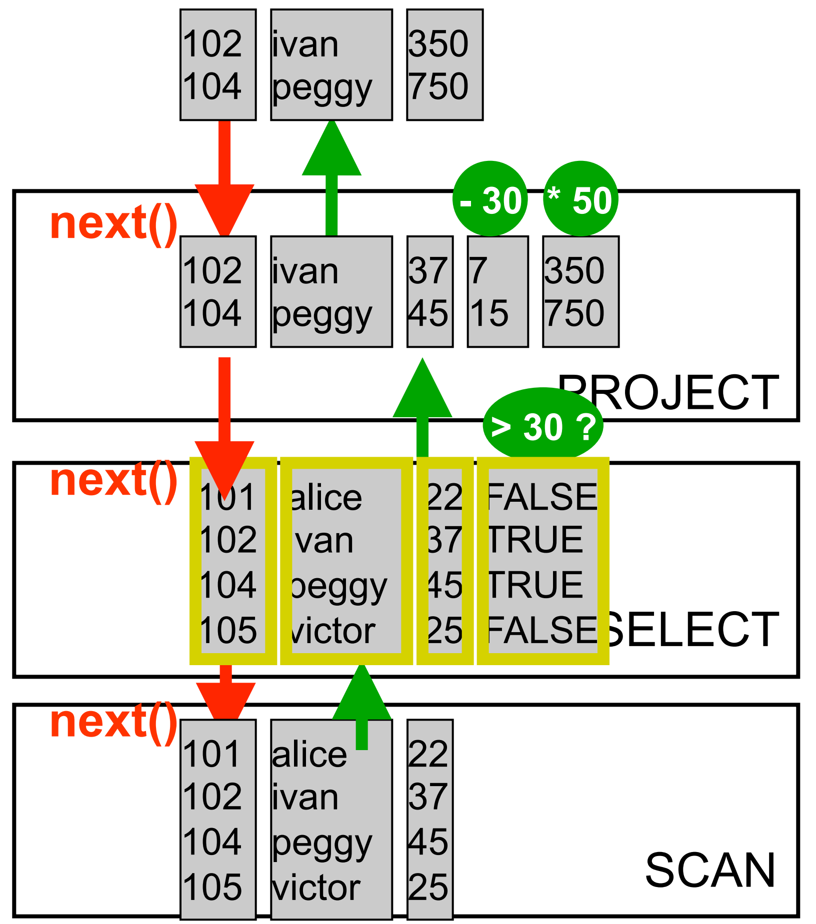
vectorwise

"Vectorized In Cache Processing"

vector = array of ~100

processed in a tight loop

CPU cache Resident



"MonetDB/X100: Hyper-Pipelining Query Execution" Boncz, Zukowski, Nes, CIDR'05

vectorwise

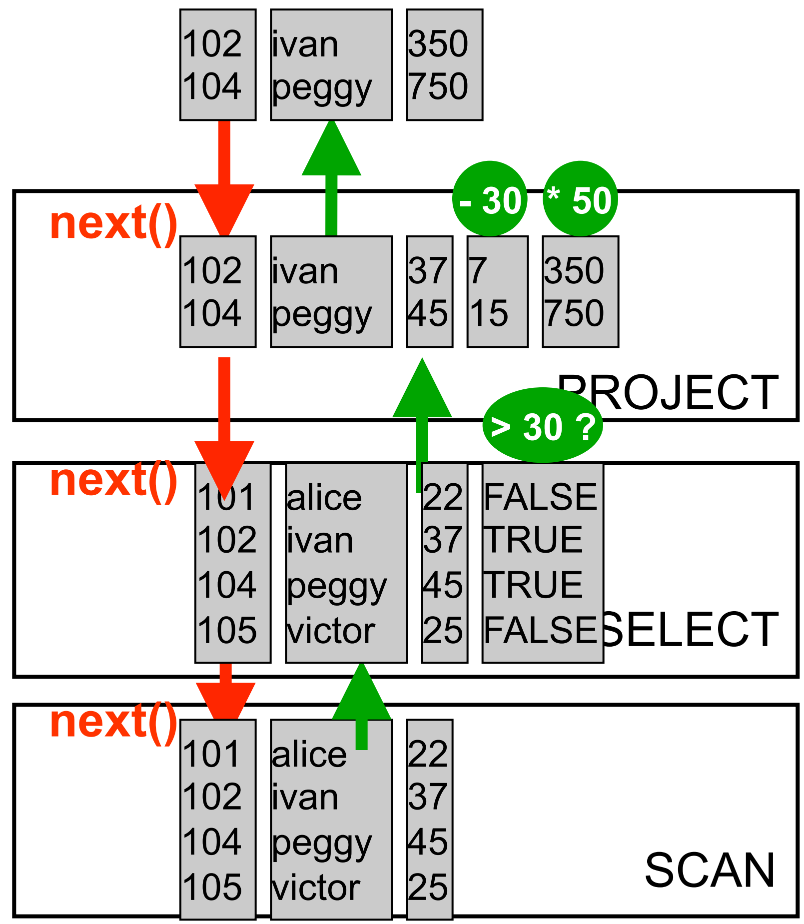
Observations:

next() called much less often → more time spent in primitives less in overhead

primitive calls process an array of values in a **loop**:

CPU Efficiency depends on "nice" code
- out-of-order execution
- few dependencies (control,data)
- compiler support

Compilers like simple loops over arrays
- loop-pipelining
- automatic SIMD



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vectorwise

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> 30 ?

FALSE
TRUE
TRUE
FALSE

```
for(i=0; i<n; i++)
   res[i] = (col[i] > x)
```

- 30

7
15

```
for(i=0; i<n; i++)
   res[i] = (col[i] - x)
```

*** 50**

350
750

```
for(i=0; i<n; i++)
   res[i] = (col[i] * x)
```

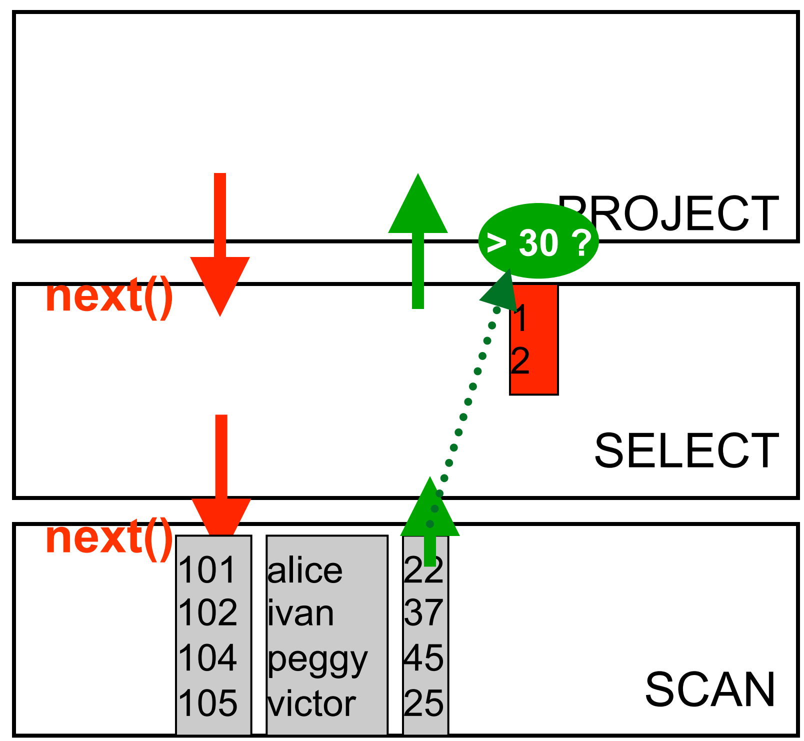
"MonetDB/X100: Hyper-Pipelining Query Execution" Boncz, Zukowski, Nes, CIDR'05

vectorwise

Tricks being played:

- Late materialization

- Materialization avoidance using selection vectors



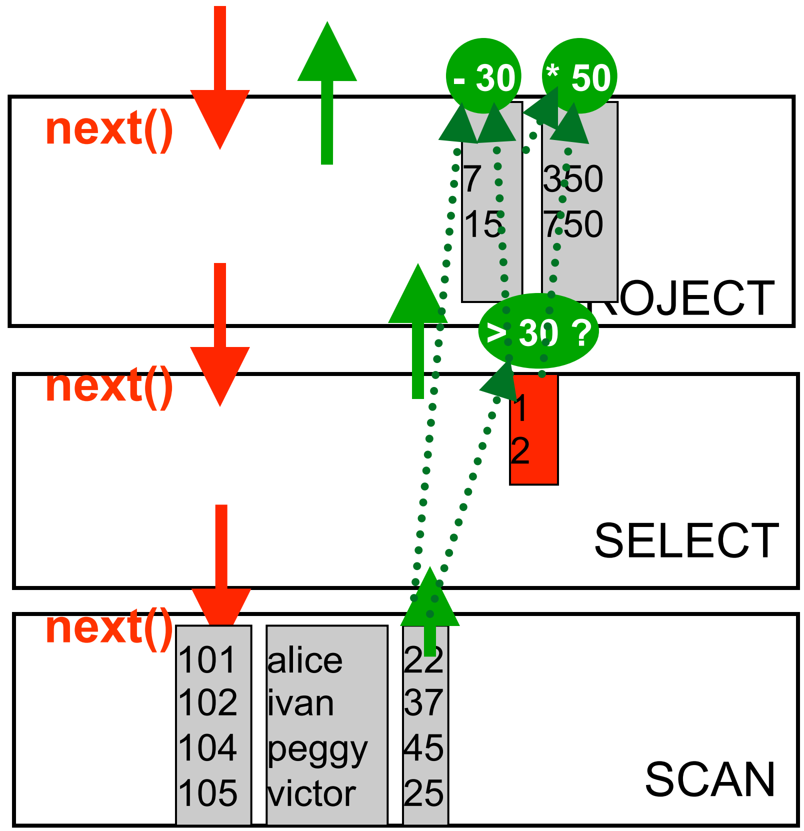
“MonetDB/X100: Hyper-Pipelining Query Execution ” Boncz, Zukowski, Nes, CIDR’ 05

```
map_mul_flt_val_flt_col(
    float *res,
    int*   sel,
    float  val,
    float *col, int n)

{
    for(int i=0; i<n; i++)
          res[i] = val * col[sel[i]];
}
```

selection vectors used to reduce vector copying

contain selected positions



"MonetDB/X100: Hyper-Pipelining Query Execution" Boncz, Zukowski, Nes, CIDR'05

vectorwise

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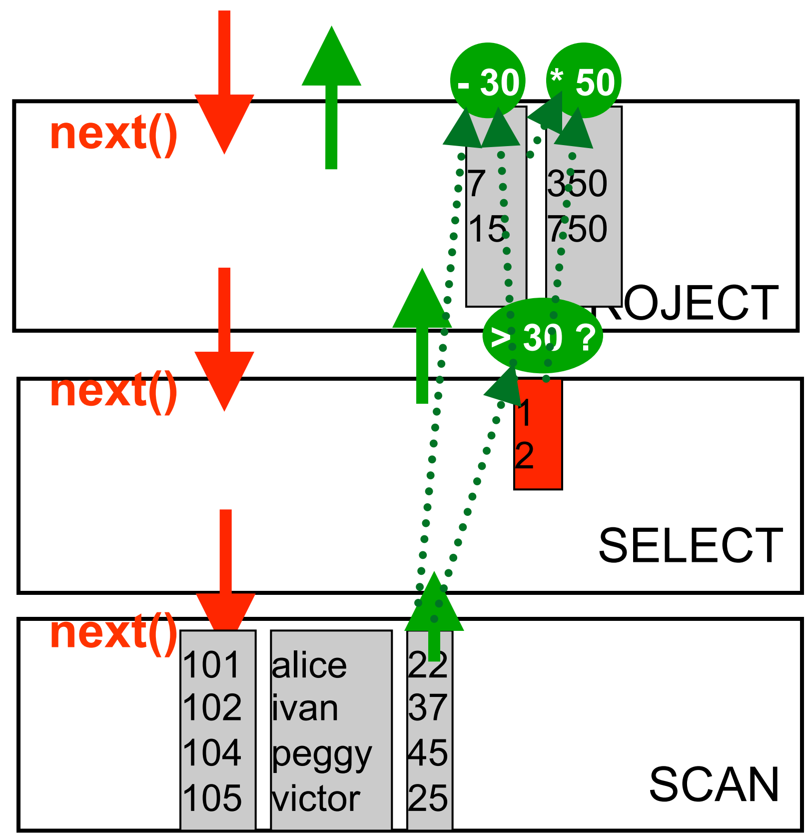
selection vectors used to reduce vector copying

contain selected positions



vectorwise

MonetDB/X100

"MonetDB/X100: Hyper-Pipelining Query Execution " Boncz, Zukowski, Nes, CIDR'05

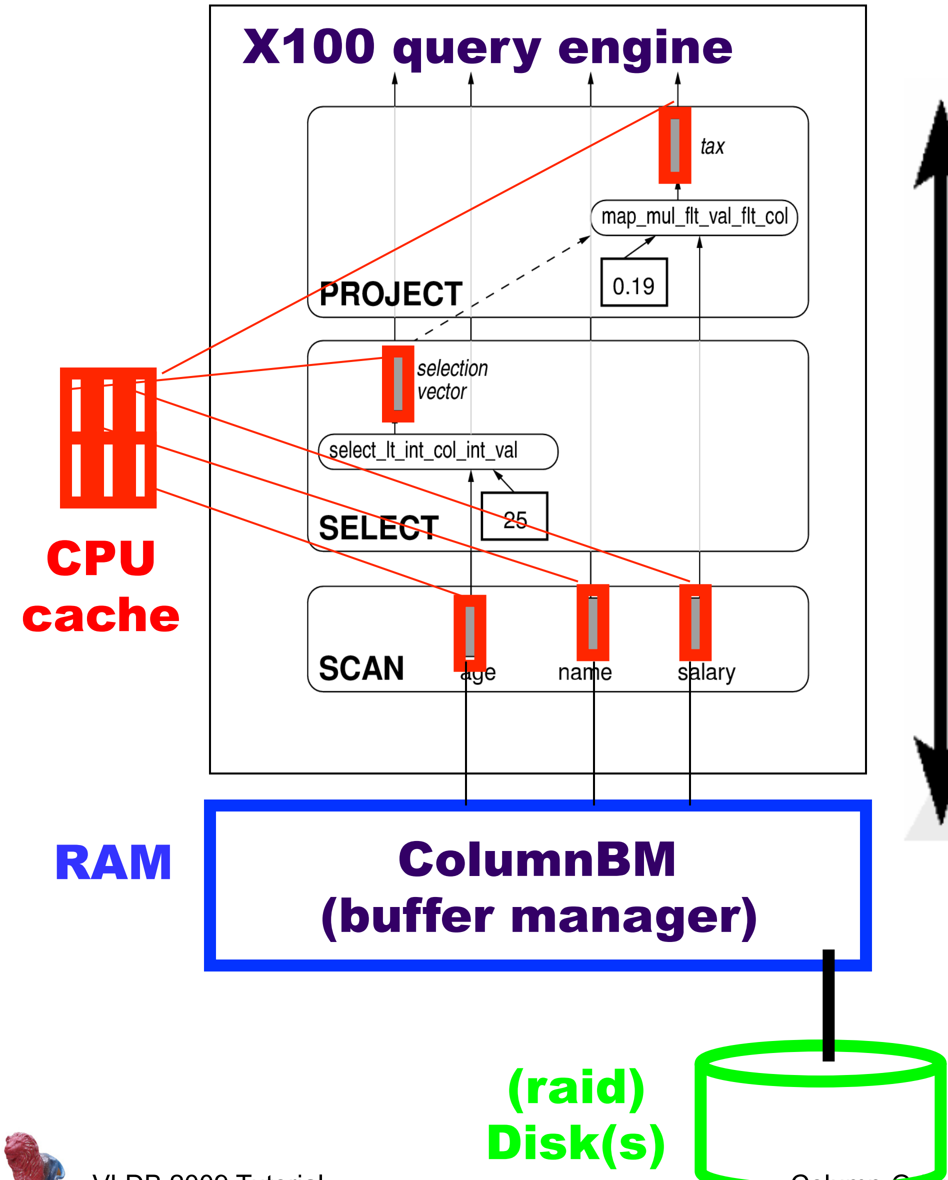
- Both efficiency
  - Vectorized primitives
- and scalability..
  - Pipelined query evaluation

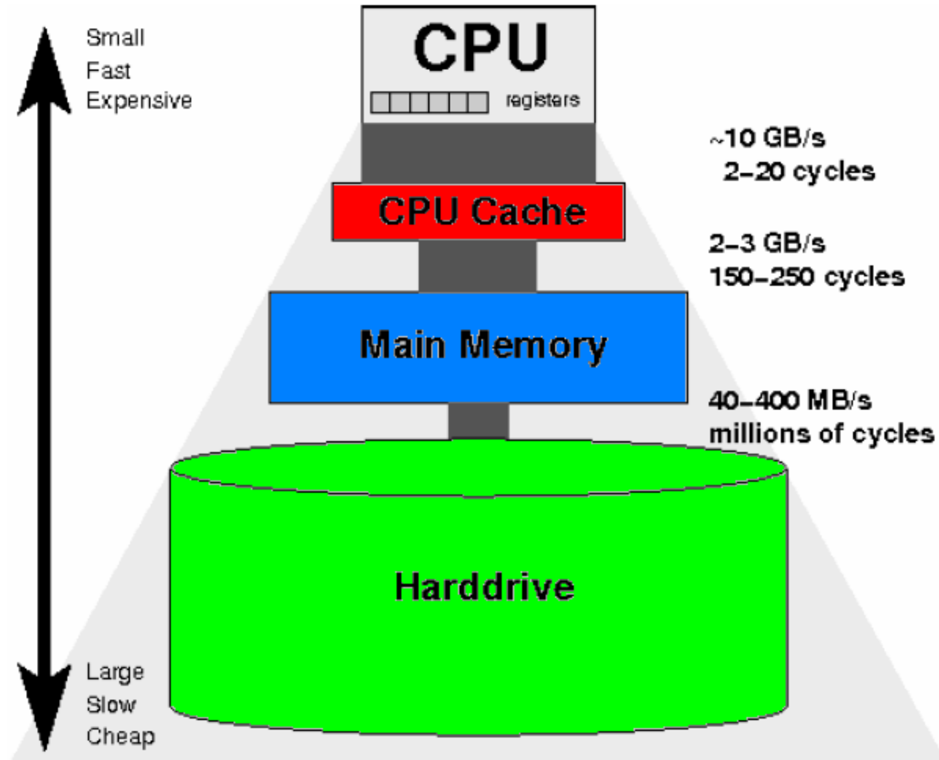
- C program: 0.2s
- MonetDB/X100: 0.6s
- MonetDB: 3.7s
- MySQL: 26.2s
- DBMS "X": 28.1s

vectorwise

Memory Hierarchy

“MonetDB/X100: Hyper-Pipelining Query Execution ” Boncz, Zukowski, Nes, CIDR’ 05





vectorwise

Memory Hierarchy

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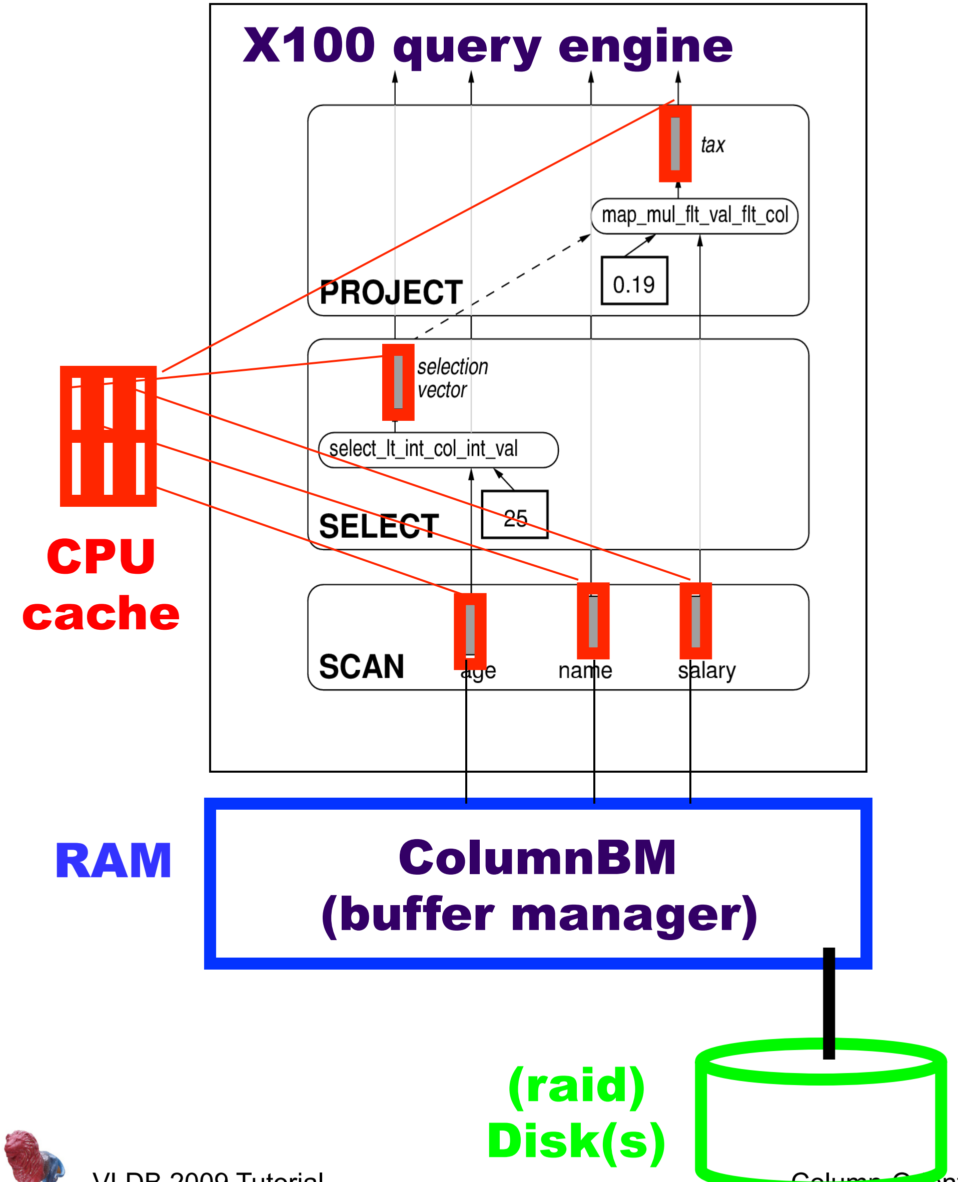


Vectors are only the in-cache representation

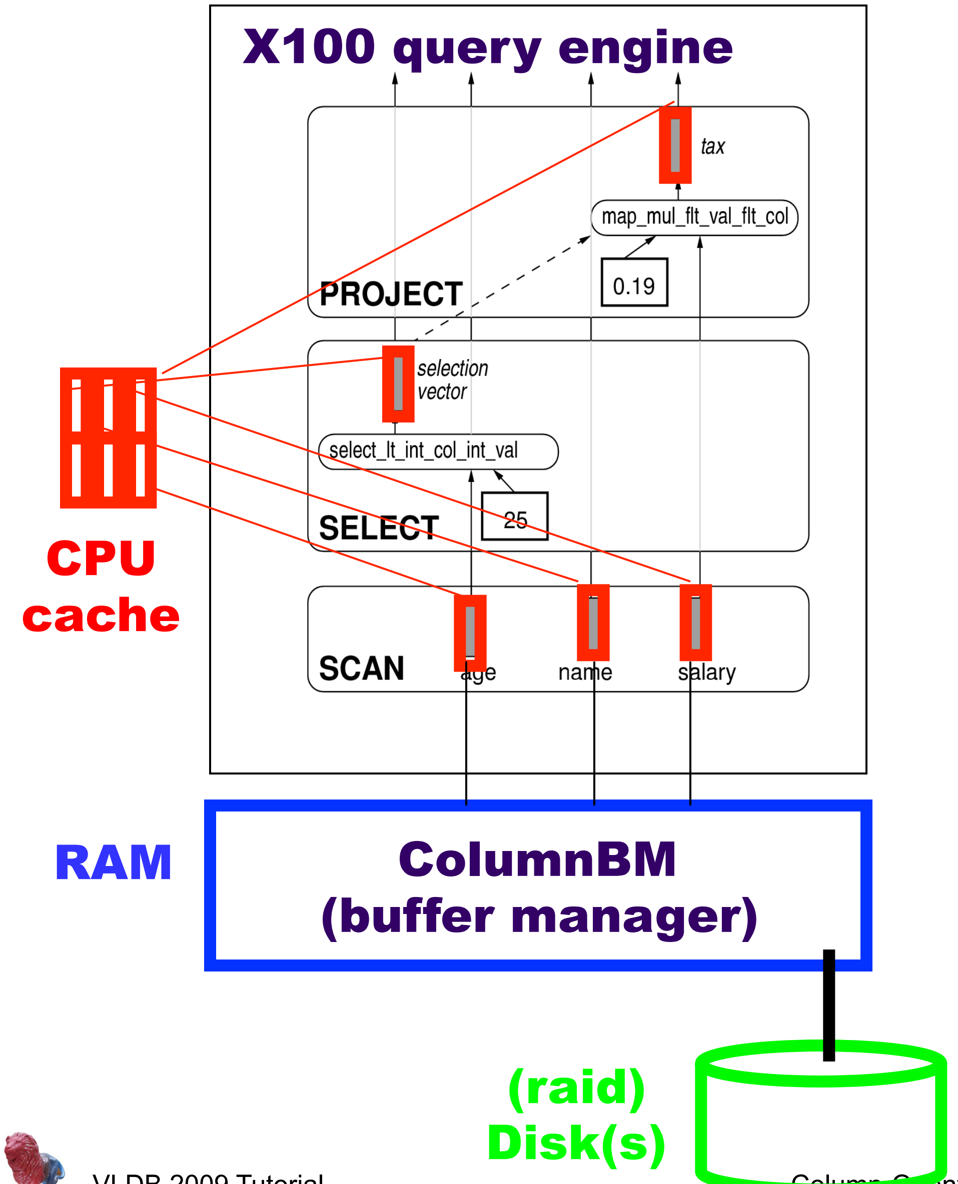
RAM & disk representation might actually be different

(vectorwise uses both PAX & DSM)

vectorwise

Optimal Vector size?

"MonetDB/X100: Hyper-Pipelining Query Execution " Boncz, Zukowski, Nes, CIDR' 05



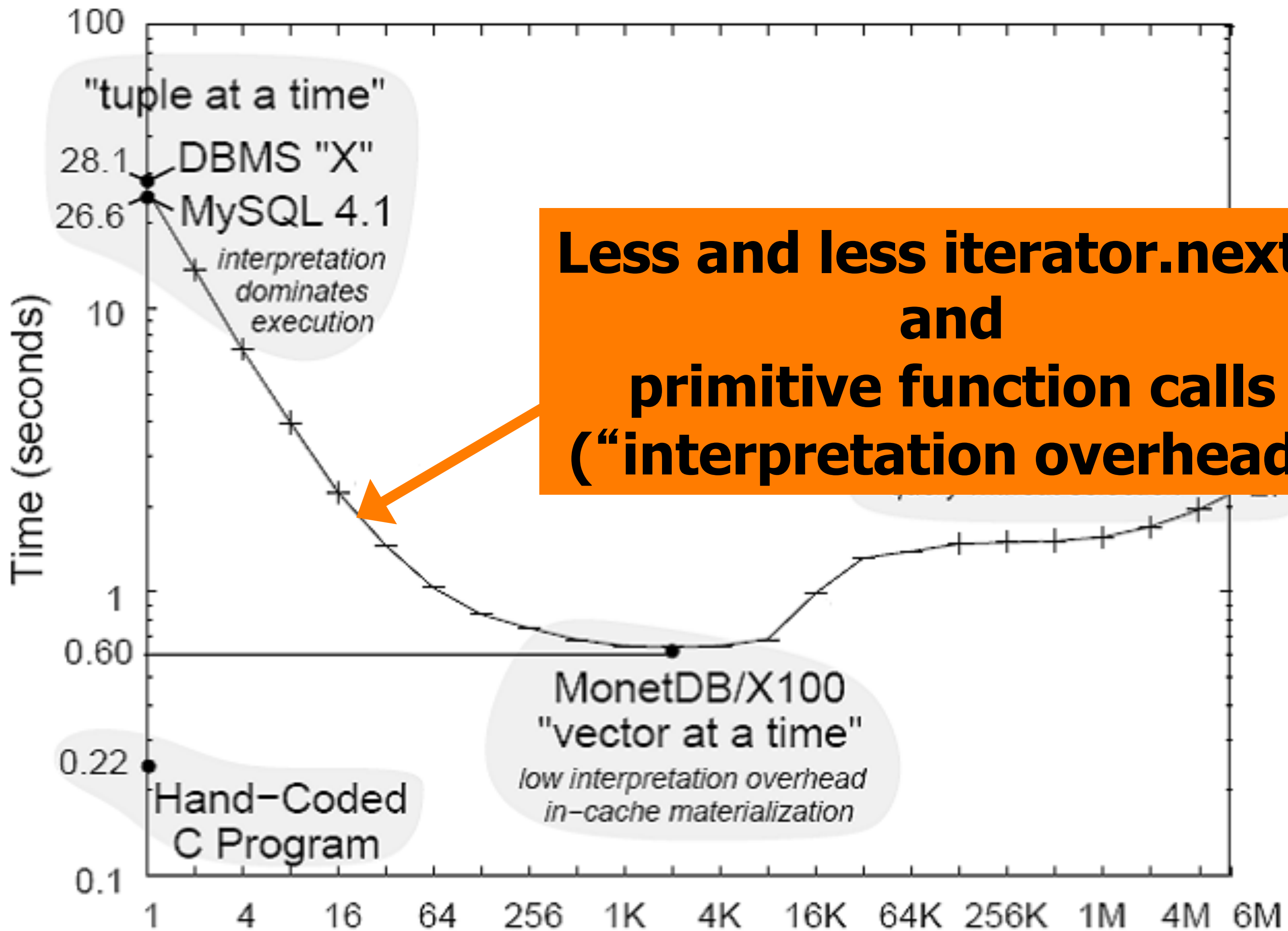
All vectors together should fit the CPU cache

Optimizer should tune this, given the query characteristics.

vectorwise

“MonetDB/X100: Hyper-Pipelining Query Execution ” Boncz, Zukowski, Nes, CIDR’05

Varying the Vector size



Less and less iterator.next() and primitive function calls (“interpretation overhead”)

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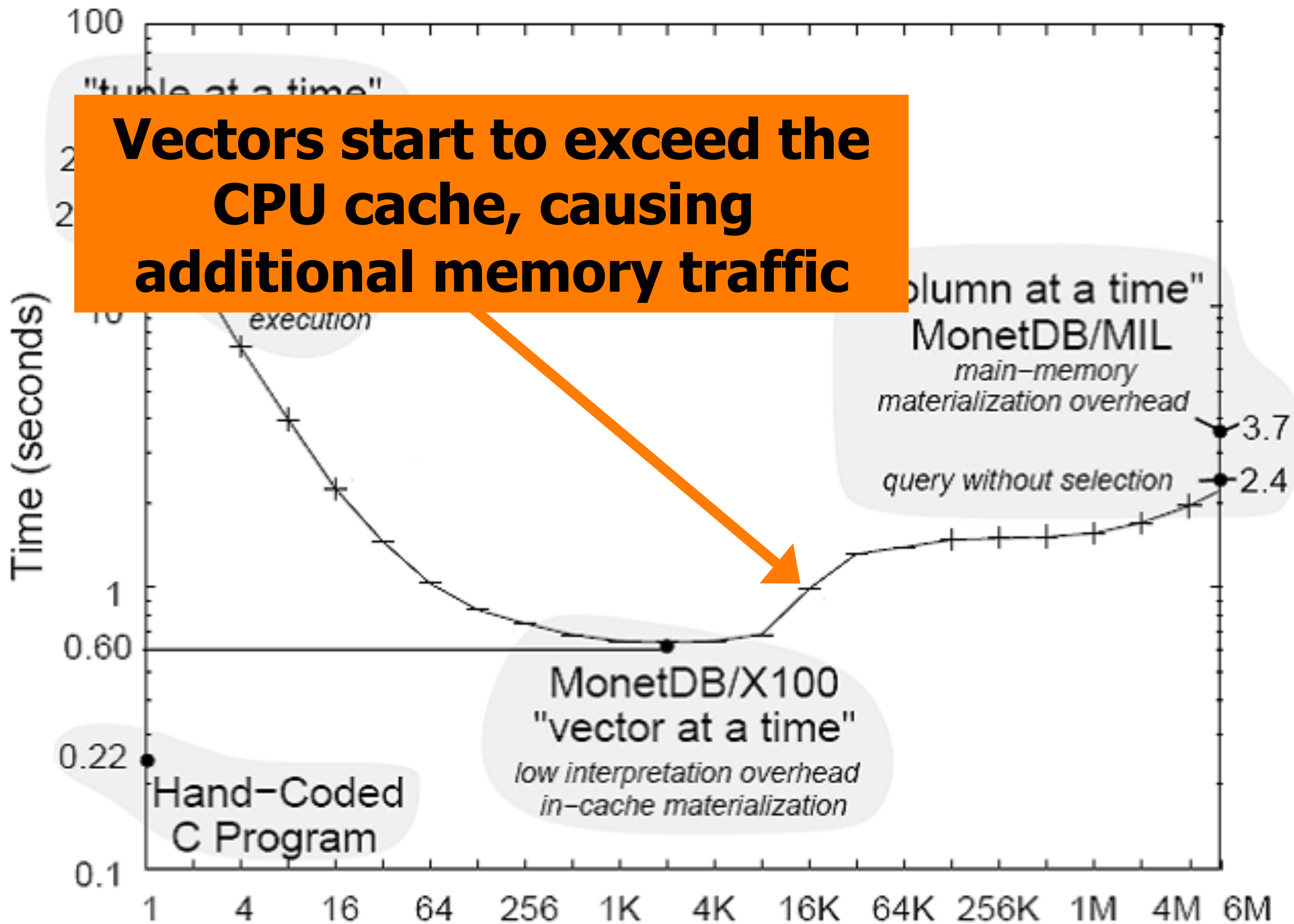
“MonetDB/X100: Hyper-Pipelining Query Execution ” Boncz, Zukowski, Nes, CIDR’05

Varying the Vector size

Vectors start to exceed the CPU cache, causing additional memory traffic



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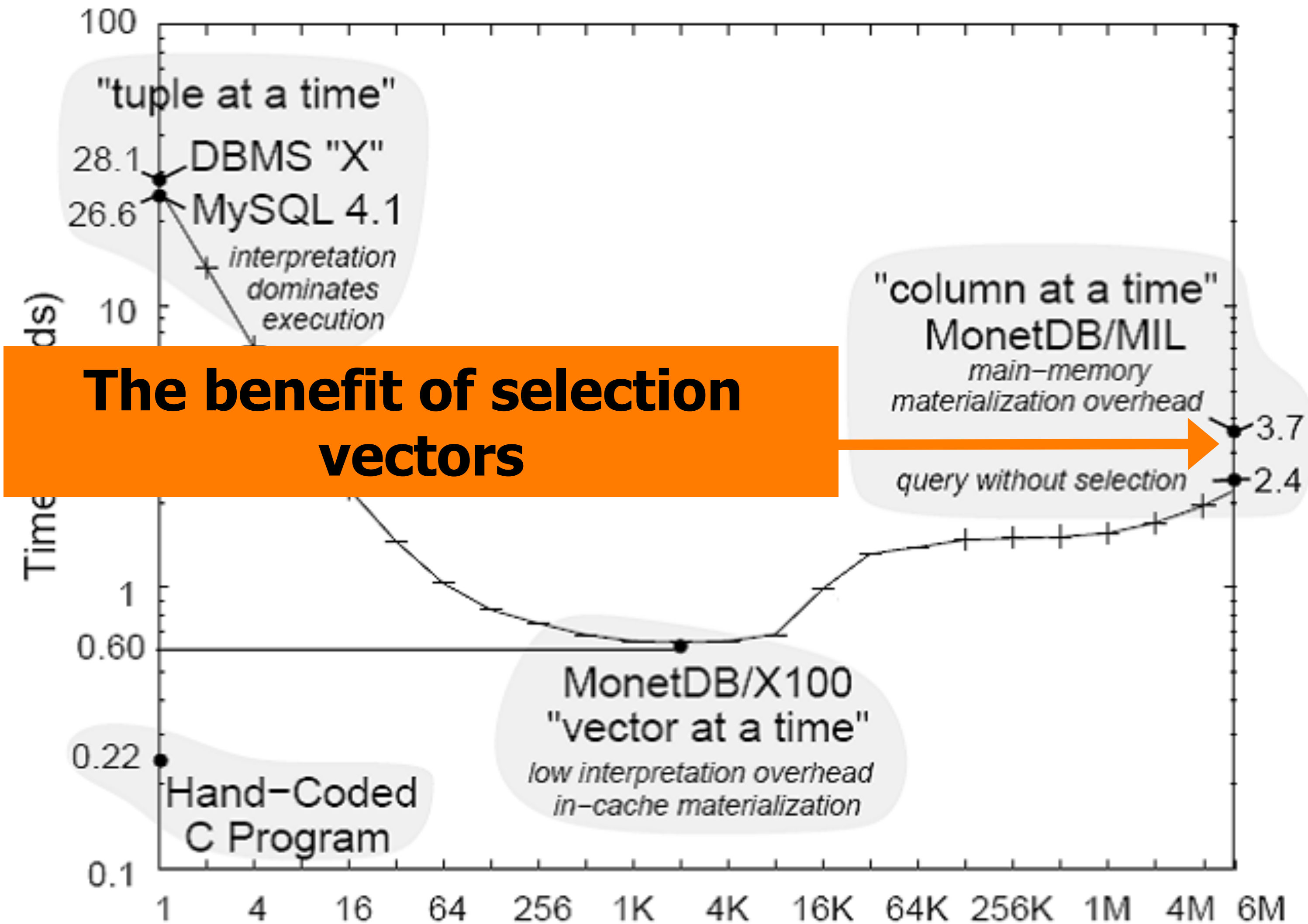
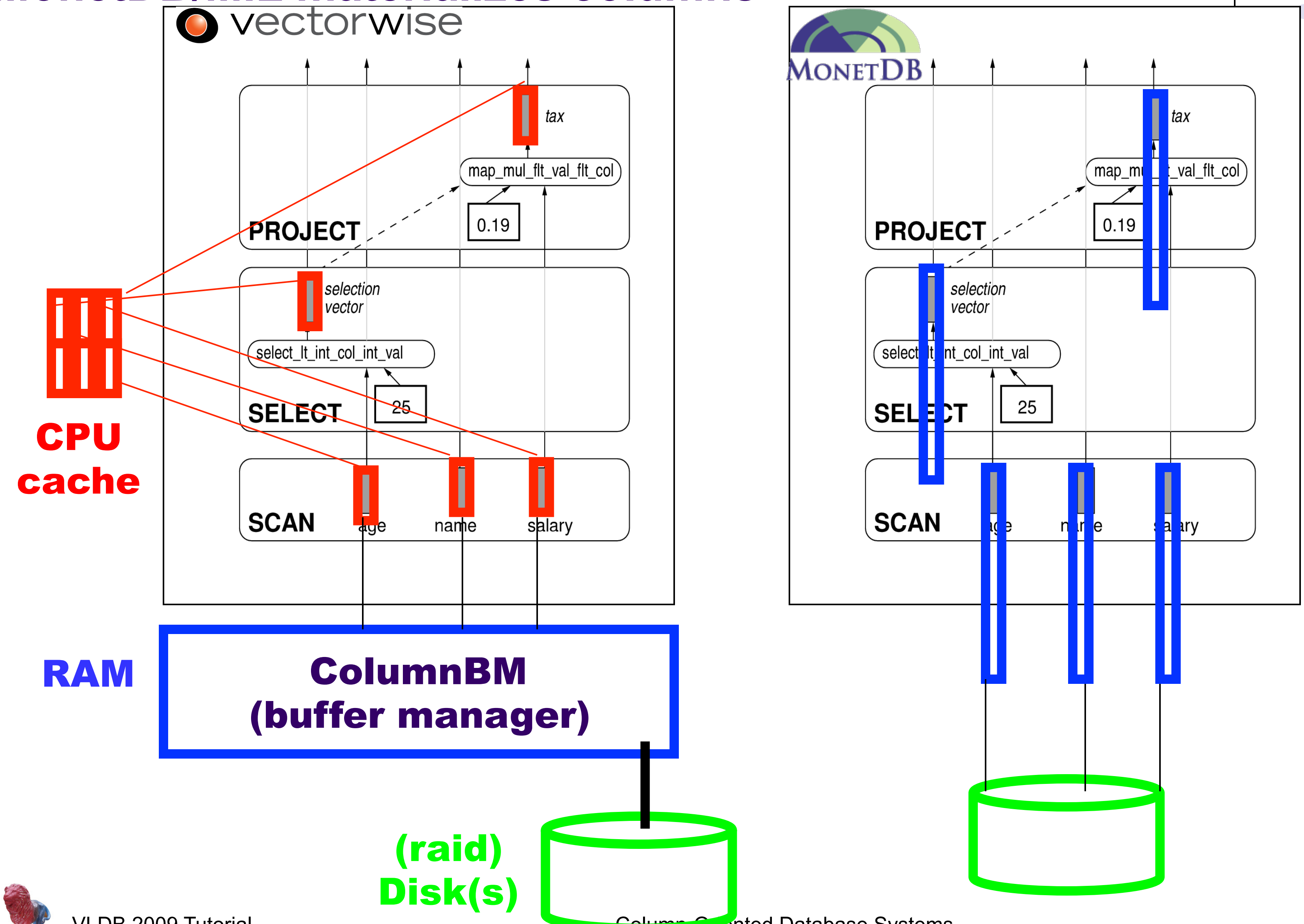
Varying the Vector size



The benefit of selection vectors

"MonetDB/X100: Hyper-Pipelining Query Execution " Boncz, Zukowski, Nes, CIDR'05

MonetDB/MIL materializes columns



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"MonetDB/X100: Hyper-Pipelining Query Execution " Boncz, Zukowski, Nes, CIDR'05

Benefits of Vectorized Processing

"Buffering Database Operations for Enhanced Instruction Cache Performance" Zhou, Ross, SIGMOD'04

"Block oriented processing of relational database operations in modern computer architectures" Padmanabhan, Malkemus, Agarwal, ICDE'01

- **100x less Function Calls**
  - iterator.next(), primitives
- **No Instruction Cache Misses**
  - High locality in the primitives
- **Less Data Cache Misses**
  - Cache-conscious data placement
- **No Tuple Navigation**
  - Primitives are record-oblivious, only see arrays
- **Vectorization allows algorithmic optimization**
  - Move activities out of the loop ("strength reduction")
- **Compiler-friendly function bodies**
  - Loop-pipelining, automatic SIMD

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"Balancing Vectorized Query Execution with Bandwidth Optimized Storage" Zukowski, CWI 2008

Vectorizing Relational Operators

- Project
- Select
  - Exploit selectivities, test buffer overflow
- Aggregation
  - Ordered, Hashed
- Sort
  - Radix-sort nicely vectorizes
- Join
  - Merge-join + Hash-join

Column-Oriented Database Systems

VLDB 2009 Tutorial

Efficient Column Store Compression

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Key Ingredients

"Super-Scalar RAM-CPU Cache Compression" Zukowski, Heman, Nes, Boncz, ICDE'06

- Compress relations on a per-column basis
  - Columns compress well
- Decompress small ***vectors*** of tuples from a column into the CPU cache
  - Minimize main-memory overhead
- Use light-weight, CPU-efficient algorithms
  - Exploit processing power of modern CPUs

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Key Ingredients

"Super-Scalar RAM-CPU Cache Compression" Zukowski, Heman, Nes, Boncz, ICDE'06

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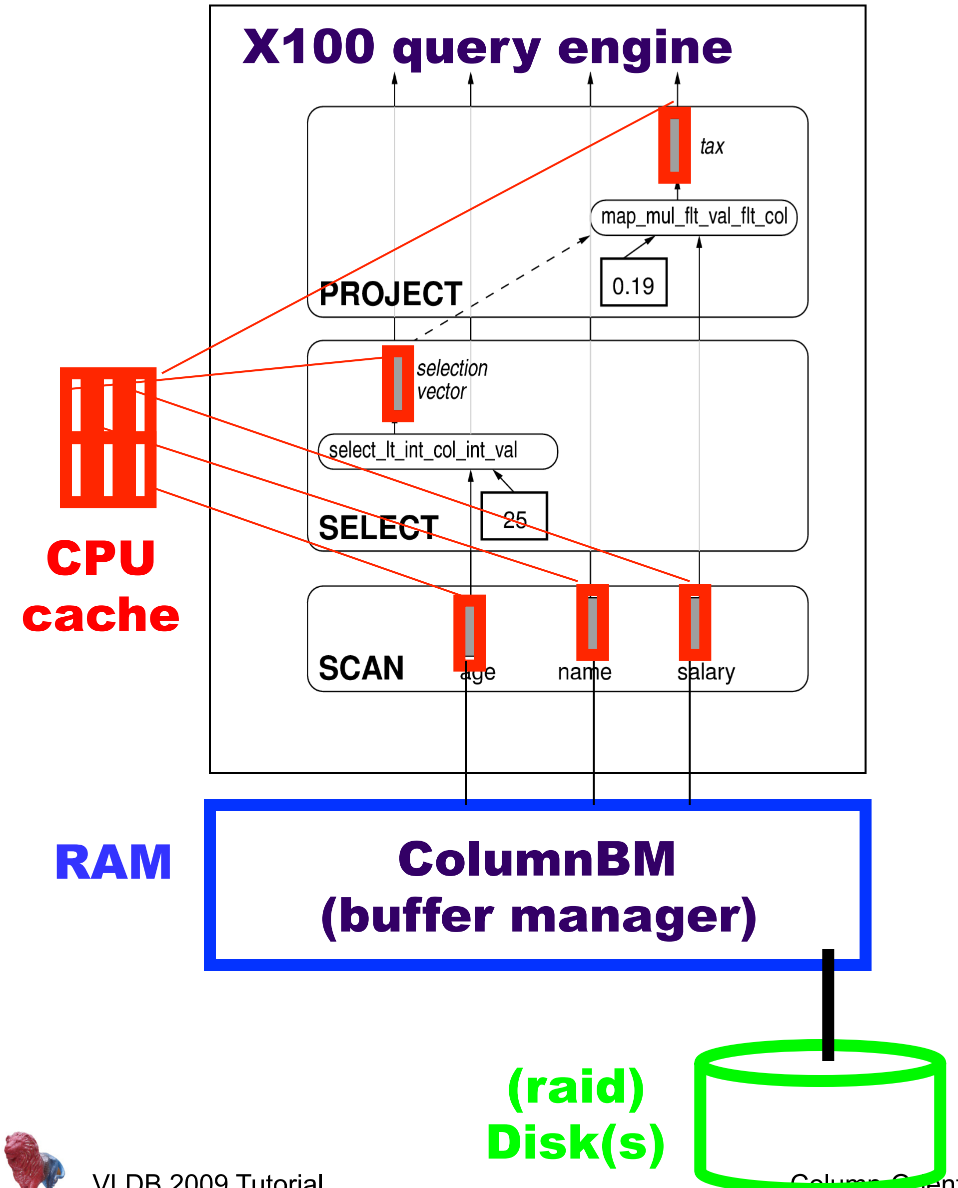
Vectorized Decompression



Idea:

decompress a vector only

compression:

-between **CPU** and RAM

-Instead of **disk** and **RAM** (classic)

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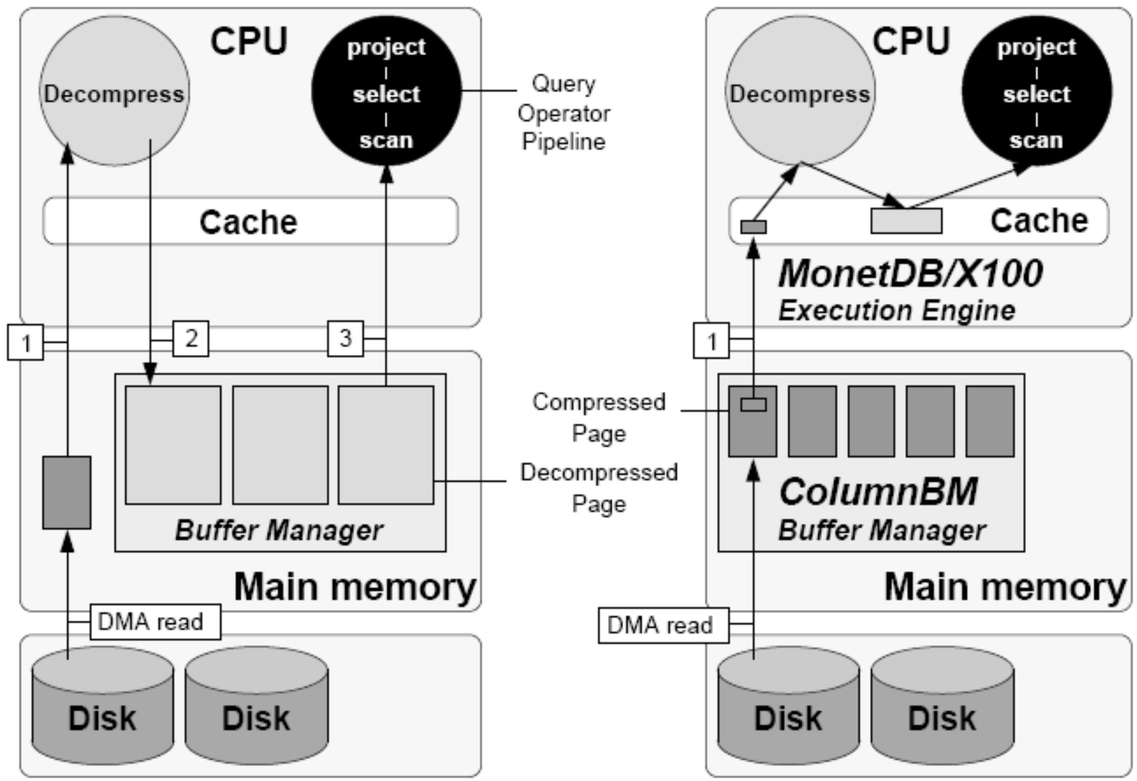
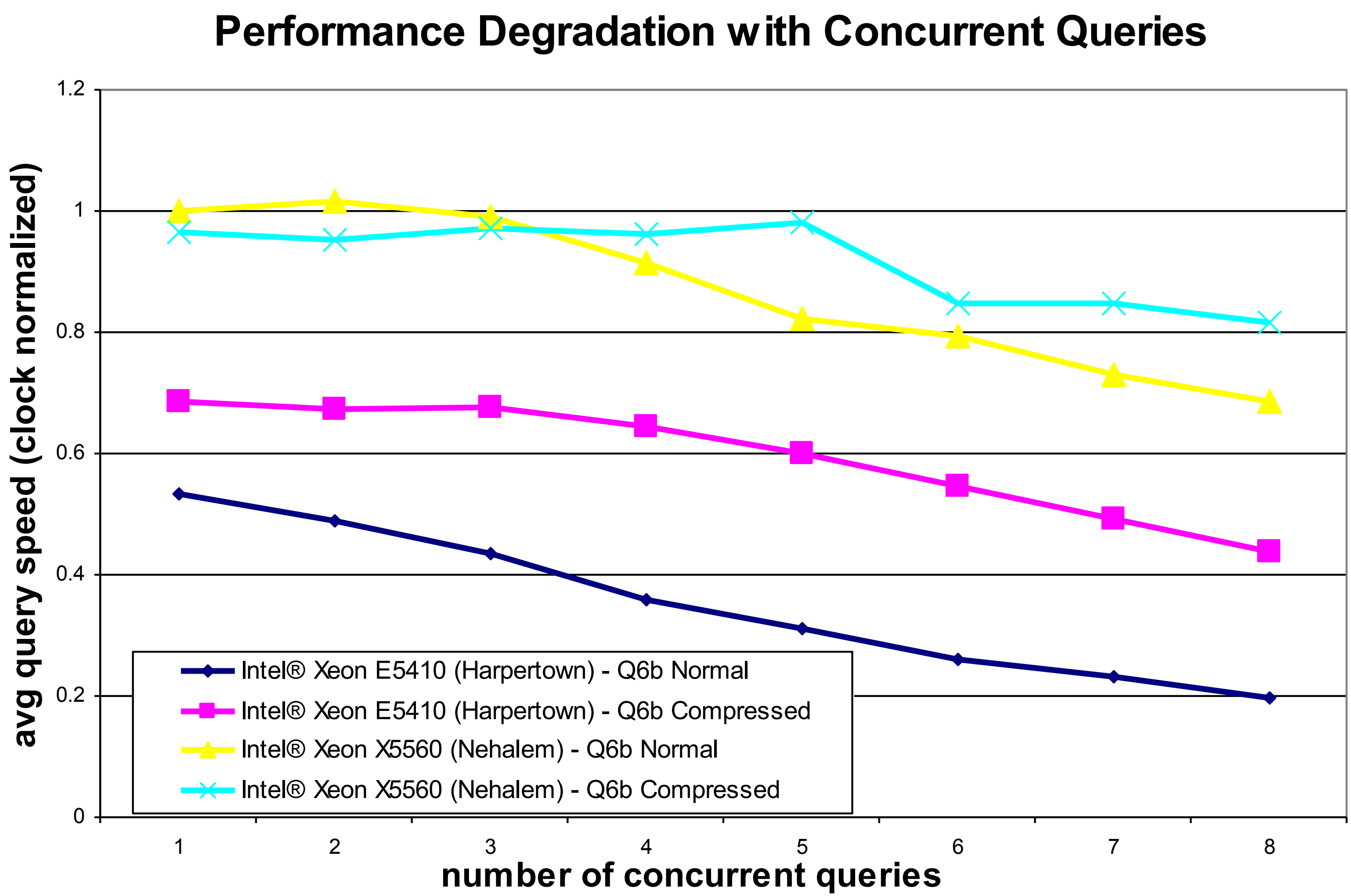
"Super-Scalar RAM-CPU Cache Compression" Zukowski, Heman, Nes, Boncz, ICDE'06

RAM-Cache Decompression



- Decompress vectors on-demand into the cache
- RAM-Cache boundary only crossed once
- **More (compressed) data cached in RAM**
- **Less bandwidth use**

Multi-Core Bandwidth & Compression



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"Super-Scalar RAM-CPU Cache Compression" Zukowski, Heman, Nes, Boncz, ICDE'06

CPU Efficient Decompression

- Decoding loop over cache-resident vectors of code words
- Avoid control dependencies within decoding loop
  - no `if-then-else` constructs in loop body
- Avoid data dependencies between loop iterations

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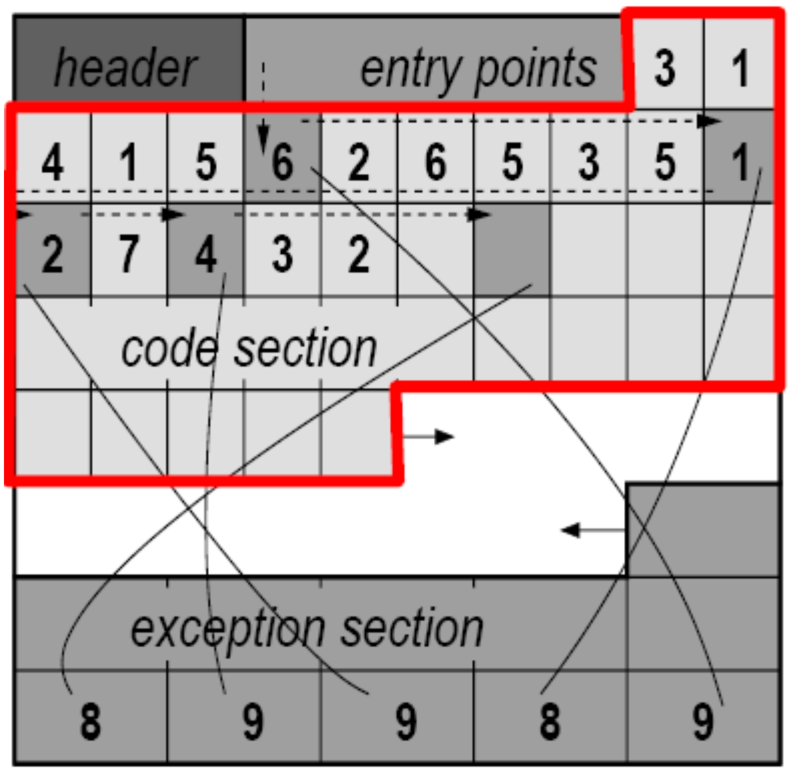
“Super-Scalar RAM-CPU Cache Compression” Zukowski, Heman, Nes, Boncz, ICDE’06

Disk Block Layout



- Forward growing section of arbitrary size **code words** (code word size fixed per block)

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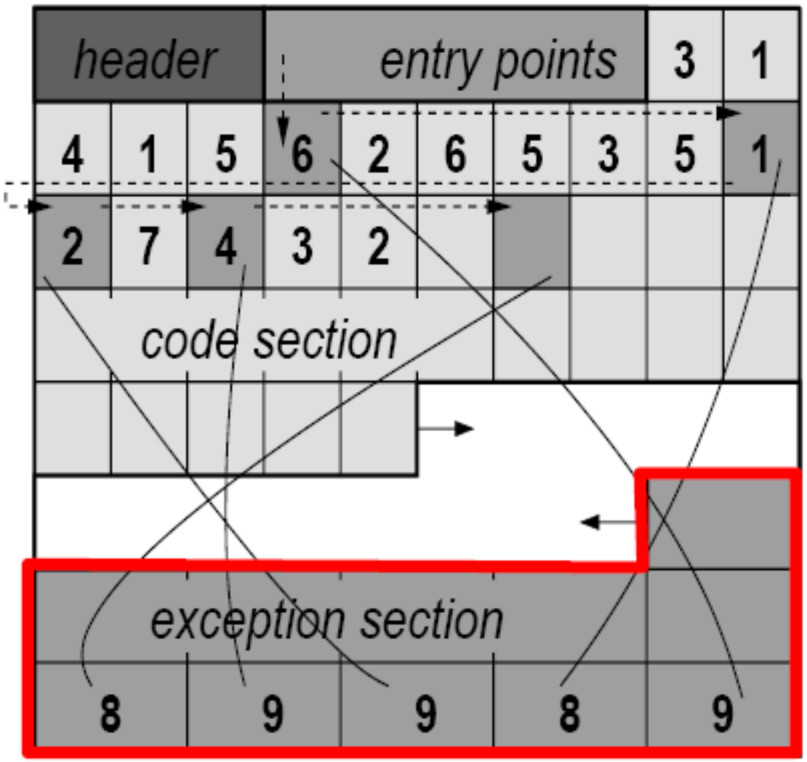
"Super-Scalar RAM-CPU Cache Compression" Zukowski, Heman, Nes, Boncz, ICDE'06

Disk Block Layout



- Forward growing section of arbitrary size code words (code word size fixed per block)
- Backwards growing **exception list**

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"Super-Scalar RAM-CPU Cache Compression" Zukowski, Heman, Nes, Boncz, ICDE'06

Naïve Decompression Algorithm

- Use reserved value from code word domain (MAXCODE) to *mark* exception positions

```
int code[n]; /* temporary machine addressable buffer */

/* blow up next vector of b-bit input code words into
   machine addressable representation */
UNPACK[b](code, input, n) ;

for(i=j=0; i<n; i++) {
     if (code[i] < MAXCODE) {
             output[i] = DECODE(code[i]);
     } else {
             output[i] = exception[--j]);
     }
}
```

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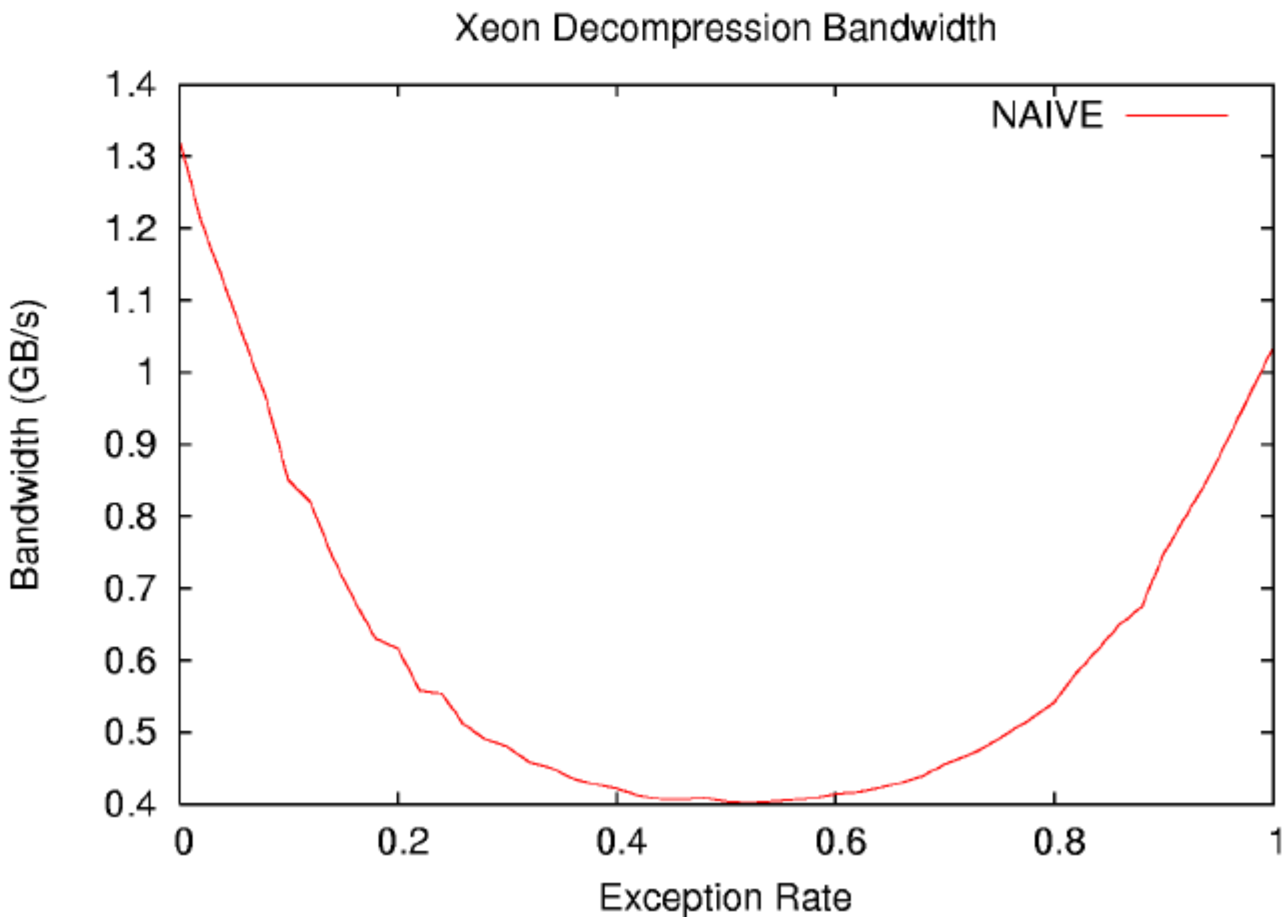
"Super-Scalar RAM-CPU Cache Compression" Zukowski, Heman, Nes, Boncz, ICDE'06

Deterioriation With Exception%



- 1.2GB/s deteriorates to 0.4GB/s

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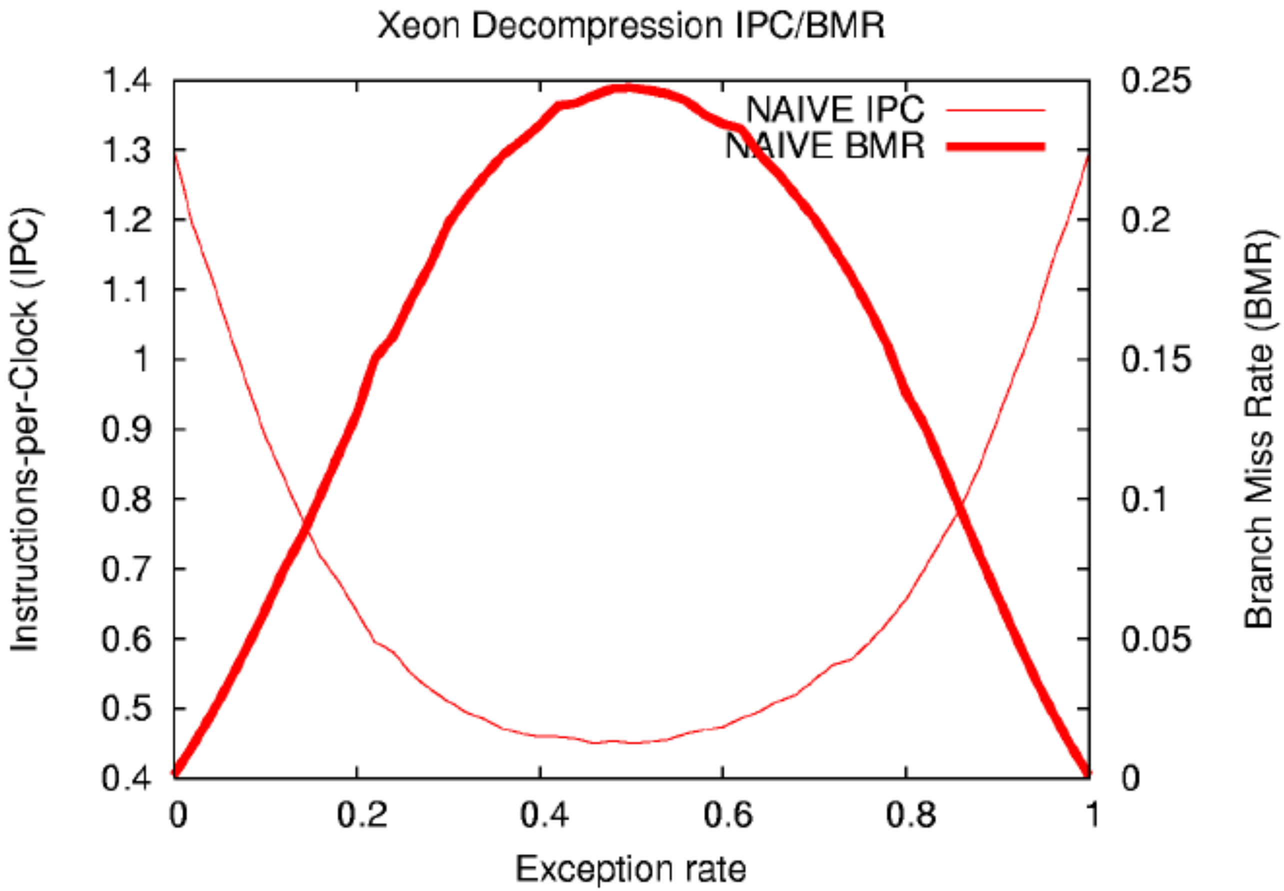
"Super-Scalar RAM-CPU Cache Compression" Zukowski, Heman, Nes, Boncz, ICDE'06

Deterioriation With Exception%



- Perf Counters: CPU mispredicts if-then-else

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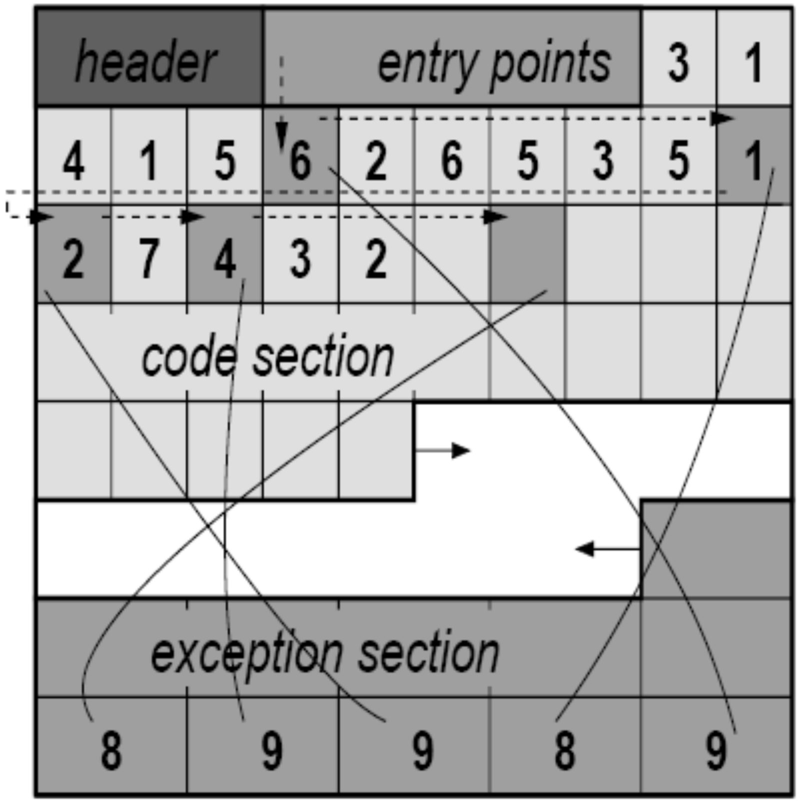
“Super-Scalar RAM-CPU Cache Compression” Zukowski, Heman, Nes, Boncz, ICDE’06

Patching



- Maintain a *patch-list* through code word section that links exception positions

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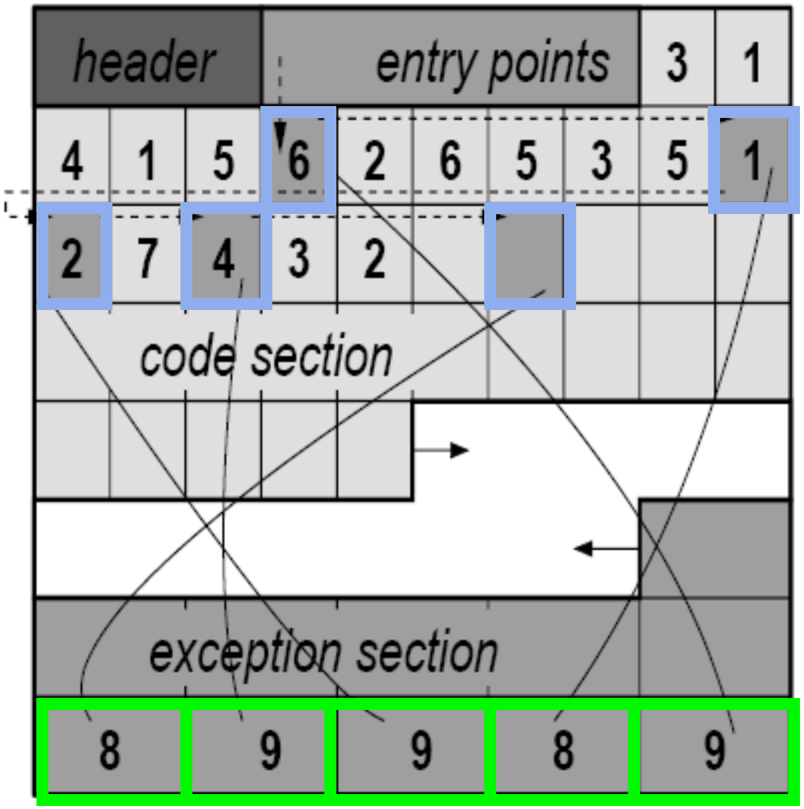
"Super-Scalar RAM-CPU Cache Compression" Zukowski, Heman, Nes, Boncz, ICDE' 06

Patching



- Maintain a *patch-list* through code word section that links exception positions
- After decoding, *patch* up the exception positions with the correct values

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"Super-Scalar RAM-CPU Cache Compression" Zukowski, Heman, Nes, Boncz, ICDE'06

Patched Decompression

```
/* initialize cur to index of first exception within codes */
int cur = first_exception;
int code[n]; /* temporary machine addressable buffer /

/* blow up next vector of b-bit input code words into machine
    addressable representation */
UNPACK[b](code, input, n) ;

/* LOOP1: decode all values */
for(int i=0; i<n; i++) {
          output[i] = DECODE(code[i]);
}

/* LOOP2: patch it up */
for(int i=1; cur < n; i++) {
          output[cur] = exception[-i];
          cur = cur + code[cur];
}
```

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"Super-Scalar RAM-CPU Cache Compression" Zukowski, Heman, Nes, Boncz, ICDE'06

Patched Decompression

```
/* initialize cur to index of first exception within codes */
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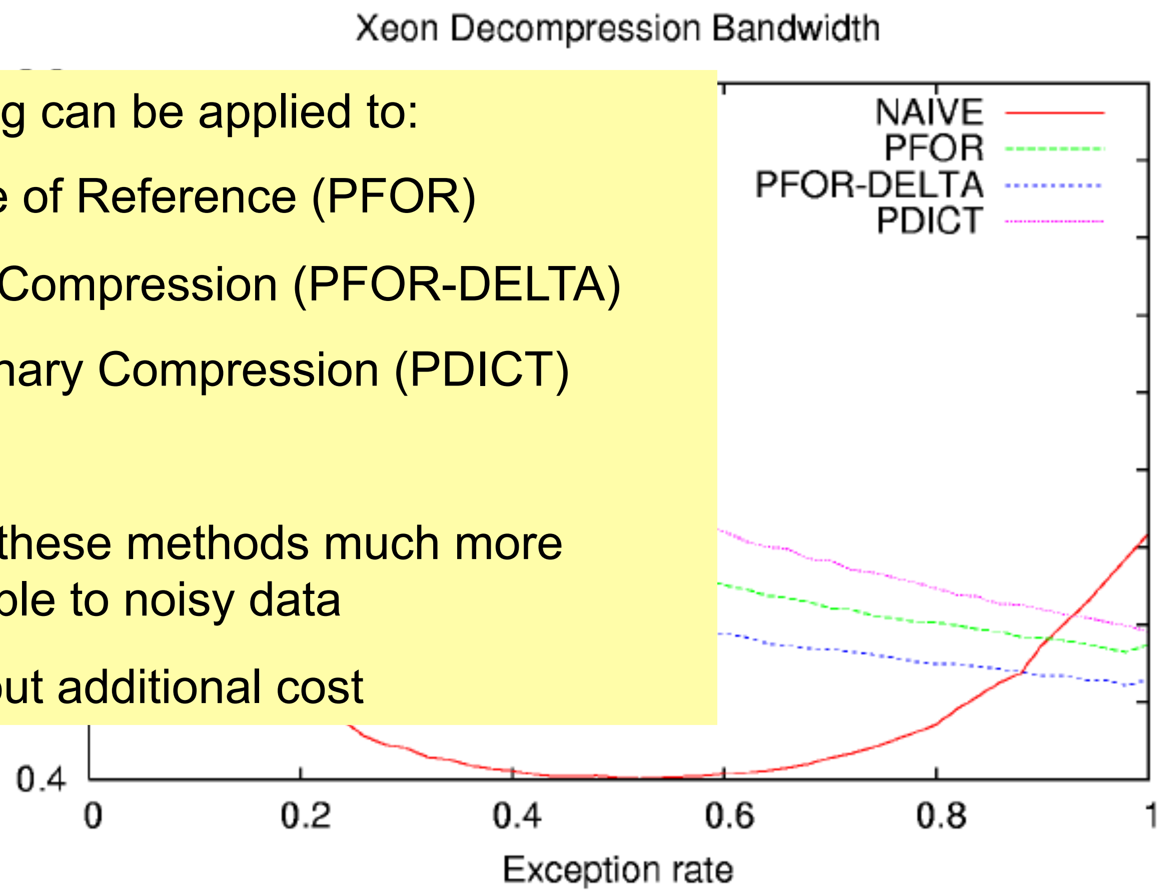
Decompression Bandwidth



Patching can be applied to:

- Frame of Reference (PFOR)
- Delta Compression (PFOR-DELTA)
- Dictionary Compression (PDICT)

Makes these methods much more applicable to noisy data

➔without additional cost

- Patching makes two passes, but is faster!

Column-Oriented Database Systems

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Conclusion

Summary (1/2)

- Columns and Row-Stores: different?
  - No fundamental differences
  - Can current row-stores simulate column-stores now?
    - not efficiently: row-stores need change
  - On disk layout vs execution layout
    - actually independent issues, on-the-fly conversion pays off
    - column favors sequential access, row random
  - Mixed Layout schemes
    - Fractured mirrors
    - PAX, Clotho
    - Data morphing

Summary (2/2)

- Crucial Columnar Techniques
  - Storage
    - Lean headers, sparse indices, fast positional access
  - Compression
    - Operating on compressed data
    - Lightweight, vectorized decompression
  - Late vs Early materialization
    - Non-join: LM always wins
    - Naïve/Invisible/Jive/Flash/Radix Join (LM often wins)
  - Execution
    - Vectorized in-cache execution
    - Exploiting SIMD

Future Work

- looking at write/load tradeoffs in column-stores
  - read-only vs batch loads vs trickle updates vs OLTP

Updates (1/3)

- Column-stores are update-in-place averse
  - In-place: I/O for each column
  - + re-compression
  - + multiple sorted replicas
  - + sparse tree indices

Update-in-place is infeasible!

Updates (2/3)

- Column-stores use differential mechanisms instead
  - Differential lists/files or more advanced (e.g. PDTs)
  - Updates buffered in RAM, merged on each query
  - Checkpointing merges differences in bulk sequentially
    - I/O trends favor this anyway
      - trade RAM for converting random into sequential I/O
      - this trade is also needed in Flash (do not write randomly!)
    - How high loads can it sustain?
      - Depends on available RAM for buffering (how long until full)
        - Checkpoint must be done within that time
        - The longer it can run, the less it molests queries
      - Using Flash for buffering differences buys a lot of time
        - Hundreds of GBs of differences per server

Updates (3/3)

- Differential transactions favored by hardware trends
- Snapshot semantics accepted by the user community
  - can always convert to serialized

    "Serializable Isolation For Snapshot Databases"
    Alomari, Cahill, Fekete, Roehm, SIGMOD'08

➔ Row stores could also use differential transactions and be efficient!
  - ➔ Implies a departure from ARIES
  - ➔ Implies a full rewrite

My conclusion:

a system that combines row- and columns needs differentially implemented transactions.

Starting from a pure column-store, this is a limited add-on.

Starting from a pure row-store, this implies a full rewrite.

Future Work

- looking at write/load tradeoffs in column-stores
  - read-only vs batch loads vs trickle updates vs OLTP
- database design for column-stores
- column-store specific optimizers
  - compression/materialization/join tricks ➔ cost models?
- hybrid column-row systems
  - can row-stores learn new column tricks?
    - Study of the minimal number changes one needs to make to a row store to get the majority of the benefits of a column-store
    - Alternative: add features to column-stores that make them more like row stores

Conclusion

- Columnar techniques provide clear benefits for:
  - Data warehousing, BI
  - Information retrieval, graphs, e-science
- A number of crucial techniques make them effective
  - Without these, existing row systems do not benefit
- Row-Stores and column-stores could be combined
  - Row-stores may adopt some column-store techniques
  - Column-stores add row-store (or PAX) functionality
- Many open issues to do research on!