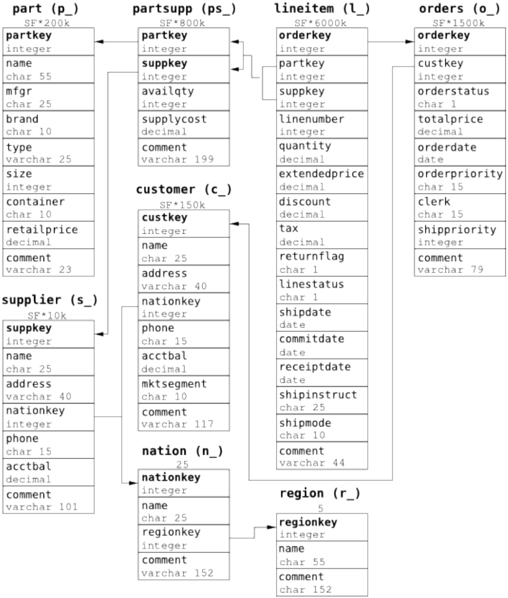
SQL

- intergalactic standard for data retrieval
- SQL is declarative (specifies rather than how to execute the query)
- supported by almost all data processing platforms
- the SQL standard grows over time: SQL-92 (basics supported by most systems), SQL:1999 (recursive CTEs, grouping sets), SQL:2003 (window functions), SQL:2006 (XML), SQL:2008, SQL:2011 (temporal support, more window functions)
- newer versions of the SQL standard are huge and many systems only support subsets
- some differences in syntax and semantics between different systems
- we use the PostgreSQL dialect, which is fairly standards-compliant

TPC-H Data Set

- TPC-H is an ad-hoc, decision support benchmark
- randomly generated data set, data set generator available
- size can be configured (scale factor 1 is around 1 GB)



Loading Data: Schema

```
create table lineitem (
   l_orderkey integer not null,
   l_partkey integer not null,
   l_suppkey integer not null,
   l_linenumber integer not null,
   l_quantity decimal(12,2) not null,
   l_extendedprice decimal(12,2) not null,
   l_discount decimal(12,2) not null,
   l_tax decimal(12,2) not null,
   l_returnflag char(1) not null,
   l_linestatus char(1) not null,
   l_shipdate date not null,
   l_commitdate date not null,
   l_receiptdate date not null,
   l_shipinstruct char(25) not null,
   l_shipmode char(10) not null,
   l_comment text not null
);
```

Data Types (PostgreSQL)

- signed integers: `smallint` (2 bytes), `integer` (4 bytes), `bigint` (8 bytes)
- fixed-precision numbers: `numeric(scale,precision)` (scale is the number of decimal digits, precision is the number of digits after the decimal separator)
- arbitrary precision numbers: `numeric` (size unbounded, very slow)
- floating point numbers: `float` (4 bytes), `double precision` (8 bytes)
- strings: `varchar(n)` (maximum length n), `char(n)` (maximum length n, blank padded, strange semantics), `text` (arbitrary length)
- other common types: `bytea` (variable-length binary array), `timestamp` (8 bytes), `date` (4 bytes), `interval` (16 bytes), `boolean` (1 byte)
- all types may be `NULL`, unless `NOT NULL` is specified
- PostgreSQL stores data in row-wise fashion
- `https://www.postgresql.org/docs/current/static/datatype.html`

Loading CSV-like Data

```
$ head -n 1 lineitem.tbl
1|15519|785|1|17| ... |egular courts above the|
$ psql tpch
tpch=# \copy lineitem from lineitem.tbl delimiter '|'
ERROR:  extra data after last expected column
CONTEXT:  COPY lineitem, line 1: "1|15519|785|1|17|24386.67|0.
tpch# \q
$ sed -i 's/|$//' lineitem.tbl
$ psql
tpch=# \copy lineitem from lineitem.tbl delimiter '|'
COPY 600572
```

- https://www.postgresql.org/docs/current/static/sql-copy.html

Basic SQL: Joins, Group By, Ordering

```
select l_orderkey, -- single line comment
    sum(l_extendedprice * (1 - l_discount)) revenue,
    o_orderdate, o_shippriority
from customer, orders, lineitem /* this is a
multi line comment */
where c_mktsegment = 'BUILDING'
and c_custkey = o_custkey
and l_orderkey = o_orderkey
and o_orderdate < date '1995-03-15'
and l_shipdate > date '1995-03-15'
group by l_orderkey, o_orderdate, o_shippriority
order by revenue desc, o_orderdate
limit 10;
```

- How many items were shipped by German suppliers in 1995?

- How many items were shipped by German suppliers in 1995?
- What are the names and account balances of the 10 customers from EUROPE in the FURNITURE market segment who have the highest account balance?

Subqueries

- subqueries can appear (almost) everywhere:

```
select n_name,
       (select count(*) from region)
from nation,
     (select *
      from region
      where r_name = 'EUROPE') region
where n_regionkey = r_regionkey
and exists (select 1
            from customer
            where n_nationkey = c_nationkey);
```

Correlated Subqueries

```
select avg(l_extendedprice)
from lineitem l1
where l_extendedprice =
      (select min(l_extendedprice)
       from lineitem l2
       where l1.l_orderkey = l2.l_orderkey);
```

- subquery is correlated if it refers to tuple form outer query (`l1.l_orderkey`)
- naive execution: execute inner query for every tuple of outer query (quadratic runtime unless index on `l_orderkey` exists)

Query Decorrelation

- queries can be rewritten to avoid correlation (some systems do this automatically):

```
select avg(l_extendedprice)
from lineitem l1,
     (select min(l_extendedprice) m, l_orderkey
      from lineitem
      group by l_orderkey) l2
where l1.l_orderkey = l2.l_orderkey
and l_extendedprice = m;
```

- decorrelate the following query

```
select c1.c_name
from customer c1
where c1.c_mktsegment = 'AUTOMOBILE'
or c1.c_acctbal >
      (select avg(c2.c_acctbal)
       from customer c2
       where c2.c_mktsegment = c1.c_mktsegment);
```

Set Operators

- UNION, EXCEPT, and INTERSECT remove duplicates

```
select n_name from nation where n_regionkey = 2
union
select n_name from nation where n_regionkey in (1, 2)
intersect
select n_name from nation where n_regionkey < 3
except
select n_name from nation where n_nationkey = 21;
```

"Set" Operators

- UNION ALL: $l + r$
- EXCEPT ALL: $\max(l - r, 0)$
- INTERSECT ALL (very obscure): $\min(l, r)$

```
select n_name from nation where n_regionkey = 2
union all
select n_name from nation where n_regionkey in (1, 2)
intersect all
select n_name from nation where n_regionkey < 3
except all
select n_name from nation where n_nationkey = 21;
```

Miscellaneous Useful Constructs

- case (conditional expressions)

```
select case when n_nationkey > 5
            then 'large' else 'small' end
from nation;
```

- coalesce(a, b): replace NULL with some other value
- cast (explicit type conversion)
- generate_series(begin,end)
- random (random float from 0 to 1):

```
select cast(random()*6 as integer)+1
from generate_series(1,10);  -- 10 dice rolls
```

Working With Strings

- concatenation:

  ```
  select 'a' || 'b';
  ```

- simple string matching:

  ```
  select 'abcfoo' like 'abc%';
  ```

- regexp string matching:

  ```
  select 'abcabc' ~ '(abc)*';
  ```

- extract substring:

  ```
  select substring('abcfoo' from 3 for 2);
  ```

- regexp-based replacement: `(str, pattern, replacement, flags)`

  ```
  select regexp_replace('ababfooab', '(ab)+', 'xy', 'g');
  ```

Sampling

- sampling modes: `bernoulli` (pick random tuples) or `system` (pick random pages)
- set random seed with optional `repeatable` setting
- supported by PostgreSQL $\geq$ 9.5:

```
select *
from nation tablesample bernoulli(5) -- 5 percent
     repeatable (9999);
```

- it is also possible to get arbitrary tuples:

```
select *
from nation
limit 10; -- 10 arbitrary rows
```

- compute the average `o_totalprice` using a sample of 1% of all orders

Views and Common Table Expressions

- like functions in “normal” programming languages
- code reuse, abstraction, readability
- in PostgreSQL, WITH is an optimization breaker, views are not

```
create view nation_europe as
  select nation.*
  from nation, region
  where n_regionkey = r_regionkey
  and r_name = 'EUROPE';
```

```
with old_orders as (
    select *
    from orders
    where o_orderdate < date '2000-01-01')
  select count(*)
  from nation_europe, customer, old_orders
  where n_nationkey = c_nationkey
  and c_custkey = o_custkey;
```

Recursive Common Table Expressions

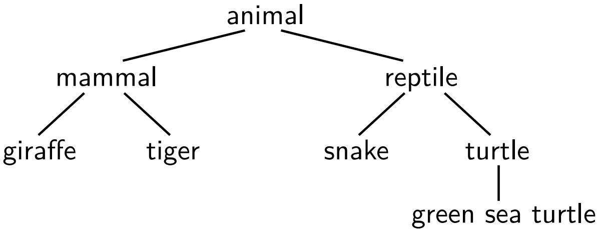
- called `recursive` but is actually iteration
- traverse hierarchical data of arbitrary depth (joins only allow a constant number of steps)

```
with recursive r (i) as (
  select 1                          -- non-recursive term
  union all
  select i+1 from r where i < 5)   -- recursive term
select * from r;
```

- algorithm:

  workingTable = *evaluateNonRecursive*()
  output *workingTable*
  while *workingTable* is not empty
    workingTable = *evaluateRecursive*(*workingTable*)
    output *workingTable*

WITH RECURSIVE ... UNION ALL




```
with recursive
 animals (id, name, parent) as (values (1, 'animal', null),
        (2, 'mammal', 1), (3, 'giraffe', 2), (4, 'tiger', 2),
        (5, 'reptile', 1), (6, 'snake', 5), (7, 'turtle', 5),
        (8, 'grean sea turtle', 7)),
  r as (select * from animals where name = 'turtle'
      union all
      select animals.*
      from r, animals
      where animals.id = r.parent)
select * from r;
```

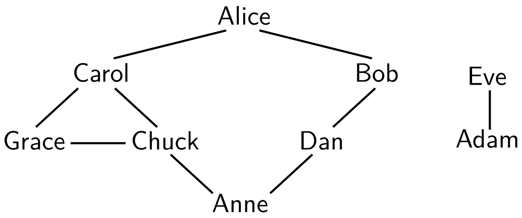
- compute all descendants of 'reptile'
- compute 10! using recursion
- compute the first 20 Fibonacci numbers ($F_1 = 1$, $F_2 = 1$, $F_n = F_{n-1} + F_{n-2}$)

Recursive Common Table Expressions with UNION

- for graph-like data UNION ALL may not terminate
- **`with recursive`** *`[non-recursive]`* **`union`** *`[recursive]`*
- allows one to traverse cyclic structures
- algorithm:

$workingTable = unique(evaluateNonRecursive())$
$result = workingTable$
while $workingTable$ is not empty
  $workingTable = unique(evaluateRecursive(workingTable)) \setminus result$
  $result = result \cup workingTable$
output $result$

WITH RECURSIVE ... UNION



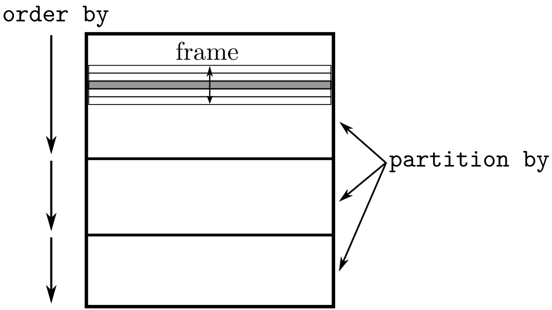

```
with recursive
 friends (a, b) as (values ('Alice', 'Bob'), ('Alice', 'Carol'),
   ('Carol', 'Grace'), ('Carol', 'Chuck'), ('Chuck', 'Grace'),
   ('Chuck','Anne'),('Bob','Dan'),('Dan','Anne'),('Eve','Adam')),
 friendship (name, friend) as -- friendship is symmetric
    (select a, b from friends union all select b, a from friends),
 r as (select 'Alice' as name
       union
       select friendship.name from r, friendship
       where r.name = friendship.friend)
select * from r;
```

Window Functions

- very versatile feature: time series analysis, ranking, top-k, percentiles, moving averages, cumulative sums
- window functions are evaluated after most other clauses (including `group by`) but before `order by`
- in contrast to aggregation, window functions do not change the input, they only compute additional columns

Window Functions: Concepts

```
select o_custkey, o_orderdate,
  sum(o_totalprice) over        -- window function
    (partition by o_custkey     -- partitioning clause
     order by o_orderdate       -- ordering clause
     range between unbounded preceding
      and current row)          -- framing clause
from customer;
```



Window Functions Framing That Ignore Framing

- ranking:
  - `rank()`: rank of the current row with gaps
  - `dense_rank()`: rank of the current row without gaps
  - `row_number()`: row number of the current row
  - `ntile(n)`: distribute evenly over buckets (returns integer from 1 to `n`)
- distribution:
  - `percent_rank()`: relative rank of the current row ((rank - 1) / (total rows - 1))
  - `cume_dist()`: relative rank of peer[1] group ((number of rows preceding or peer with current row) / (total rows))
- navigation in partition:
  - `lag(expr, offset, default)`: evaluate expr on preceding row in partition
  - `lead(expr, offset, default)`: evaluate expr on following row in partition

[1] Rows with equal partitioning and ordering values are peers.

- determine medals based on number of orders, example output:

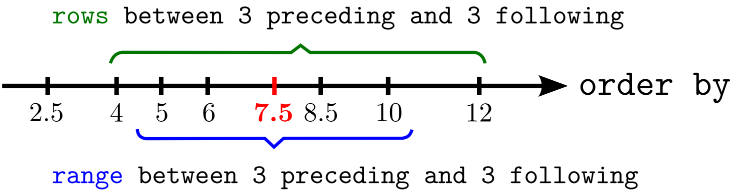
```
 custkey | count | medal
---------+-------+--------
    8761 |    36 | gold
   11998 |    36 | gold
    8362 |    35 | bronze
    4339 |    35 | bronze
     388 |    35 | bronze
    3151 |    35 | bronze
    9454 |    35 | bronze
```

- yearly (`extract(year from o_orderdate)`) change in revenue percentage (`sum(o_totalprice)`), example output:

```
  y   |     revenue     | pctchange
------+-----------------+-----------
 1992 | 3249822143.71 |
 1993 | 3186680293.06 |     -1.94
 1994 | 3276391729.79 |      2.82
 1995 | 3269894993.32 |     -0.20
 1996 | 3227878999.30 |     -1.28
 1997 | 3212138221.07 |     -0.49
 1998 | 1933789650.38 |    -39.80
```

Window Functions: Framing

- `current row`: the current row (including all peers in range mode)
- `unbounded preceding`: first row in the partition
- `unbounded following`: last row in the partition



- default frame (when an `order by` clause was specified): `range between unbounded preceding and current row`
- default frame (when no `order by` clause was specified): `range between unbounded preceding and unbounded following`
- complex frame specifications are not yet supported by PostgreSQL

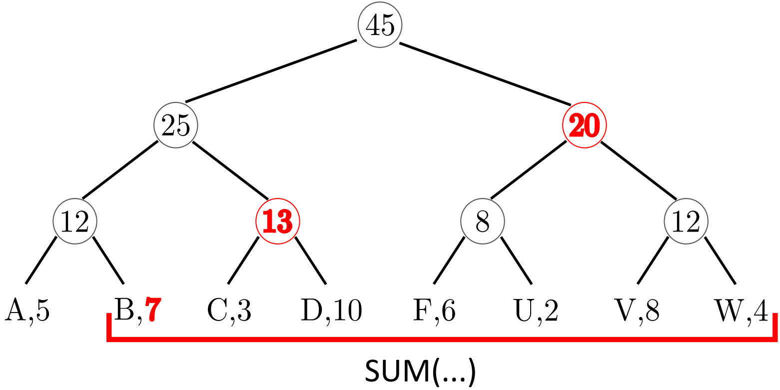
Window Functions With Framing

- aggregates (`min`, `max`, `sum`, ...):
  compute aggregate over all tuples in current frame
- navigation in frame:
  `first_value(expr)`, `last_value(expr)`, `nth_value(expr, nth)`:
  evaluate `expr` on first/last/`nth` row of the frame

- compute the cumulative customer spending (`sum(o_totalprice)`) over time (`o_orderdate`)
- for each customer from GERMANY compute the cumulative spending (`sum(o_totalprice)`) by year (`extract(year from o_orderdate)`, example output:

```
 custkey |  yr  | running_sum
---------+------+-------------
      62 | 1992 |   169991.32
      62 | 1993 |   344376.79
      62 | 1994 |   433638.98
      62 | 1995 |   960047.31
      62 | 1996 |  1372061.28
      62 | 1997 |  1658247.25
      62 | 1998 |  2055669.94
      71 | 1992 |   403017.41
      71 | 1993 |   751256.86
      71 | 1994 |  1021446.72
      71 | 1995 |  1261012.10
```

Efficient Evaluation Using Segment Tree



Statistical Aggregates

- `stddev_samp(expr)`: standard deviation
- `corr(x, y)`: correlation
- `regr_slope(y, x)`: linear regression slope
- `regr_intercept(y, x)`: linear regression intercept

Ordered-Set Aggregates

- aggregate functions that require materialization/sorting and have special syntax
- `mode()`: most frequently occurring value
- `percentile_disc(p)`: compute discrete percentile ($p \in [0, 1]$)
- `percentile_cont(p)`: compute continuous percentile ($p \in [0, 1]$), may interpolate, only works on numeric data types

```
select percentile_cont(0.5)
    within group (order by o_totalprice)
from orders;

select o_custkey,
 percentile_cont(0.5) within group (order by o_totalprice)
from orders
group by o_custkey;
```

Grouping Sets, Rollup, Cube

- aggregate across multiple dimensions, e.g., revenue by year, by customer, by supplier
- specify multiple groupings:
  group by grouping sets ((a, b), (a), ())
- hierarchical groupings:
  group by rollup (a, b)
- both are equivalent to:

```
select a, b, sum(x) from r group by a, b
union all
select a, null, sum(x) from r group by a
union all
select null, null, sum(x) from r;
```

- all (2^n) groupings:
  group by cube (a, b) is equivalent to
  group by grouping sets ((a, b), (a), (b), ())

- aggregate revenue (`sum(o_totalprice)`): total, by region (`r_name`), by name (`n_name`), example output:

```
    revenue     |         region          |         nation
----------------+-------------------------+-------------------------
   836330704.31 | AFRICA                  | ALGERIA
   902849428.98 | AFRICA                  | ETHIOPIA
   784205751.27 | AFRICA                  | KENYA
   893122668.52 | AFRICA                  | MOROCCO
   852278134.31 | AFRICA                  | MOZAMBIQUE
  4268786687.39 | AFRICA                  |
...
 21356596030.63 |                         |
```

References

- SQL reference (PostgreSQL):
  https://www.postgresql.org/docs/current/static/sql.html
- basic SQL (in German):
  Datenbanksysteme: Eine Einführung, Alfons Kemper and Andre Eickler, 10th edition, 2015
- Joe Celko's SQL for Smarties, Joe Celko, 5th edition, 2014
- SQL cookbook, Anthony Molinaro, 2005

Why Database Clusters?

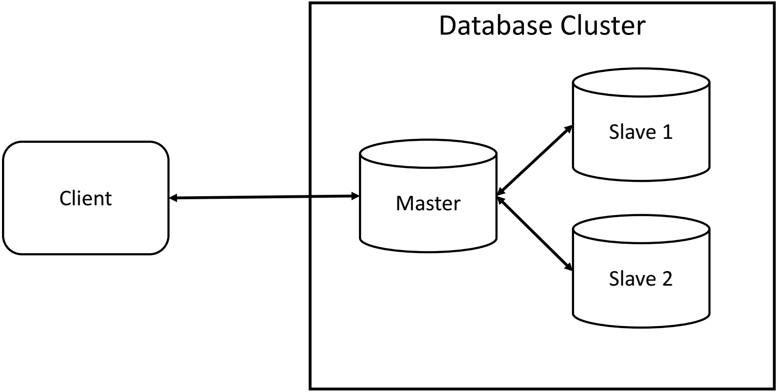
Limitations of a single machine:

- space (a few tera bytes)
- performance (hundreds of GFLOPS)
- geo-locality (speed of light)
- no redundancy (in case of failures)

Therefore, we need to use multiple machines.

Properties of Database Clusters

- transparent for the user (cluster presents itself as a single system)
- consistency vs. fussy consistency (ACID vs. BASE)



Properties of Database Clusters

ACID

- **A**tomicity: a transaction is either executed completely or not at all
- **C**onsistency: transactions can not introduce inconsistencies
- **I**solation: concurrent transactions can not see each other
- **D**urability: all changes of a transaction are durable

Properties of Database Clusters

BASE

- **B**asically **A**vailable: requests may fail
- **S**oft state: the system state may change over time
- **E**ventual consistency: once the system stops receiving input, it will eventually become consistent

Properties of Database Clusters

Providing ACID guarantees slows down the database, as more synchronization is required. **BUT**:

- BASE does not provide a consistent view of the data, which can lead to subtile bugs or confuse customers
- BASE can simply not be used for many critical systems (e.g., banking)
- before using BASE, be sure that you really do need the performance and don't need ACID guarantees. otherwise, you will end up implementing ACID on the application layer

End of Transaction Handling

Just like in a non-distributed system, a transaction has to be atomic. There are two options for ending a transaction:

commit the transaction was successful and all constraints are fulfilled: it has to become persistent and visible to all nodes of the cluster

abort the transaction failed or violates a constraint: it has to be undone on all nodes of the cluster

Problem: the nodes of a distributed system can crash independently

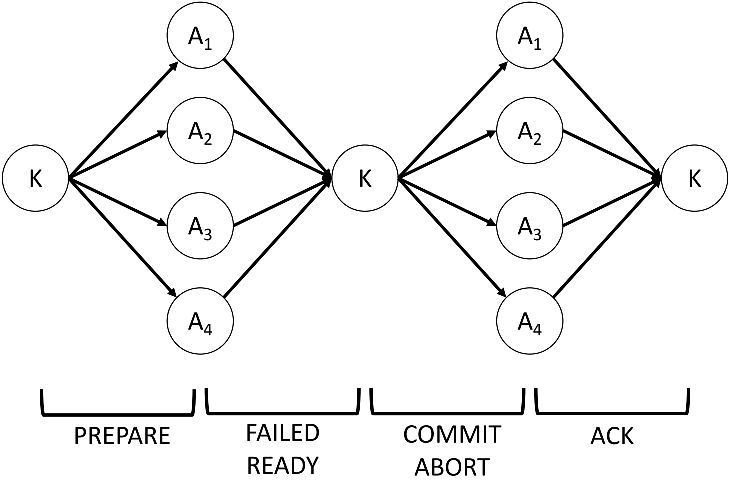
End of Transaction Handling

Solution: Two Phase Commit Protocol (2PL).

- 2PL ensures the atomic property of distributed transactions
- one node acts as a coordinator
- it allows n agents of a system $A_1, A_2, .., A_n$, which participated in a transaction T to either all persist the changes of T or all discard the changes of T

Two Phase Commit

Message flow in 2PL with 4 agents:



Two Phase Commit

Potential points of failure in 2PL:

- crash of the coordinator
- crash of an agent
- lost messages

Replication

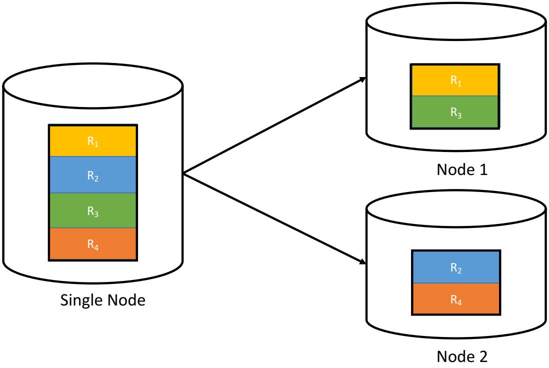
Every machine in the cluster has a (consistent) copy of the entire dataset.

- improved query throughput
- can accommodate node failures
- solves locality issue

Horizontal Partitioning (Sharding)

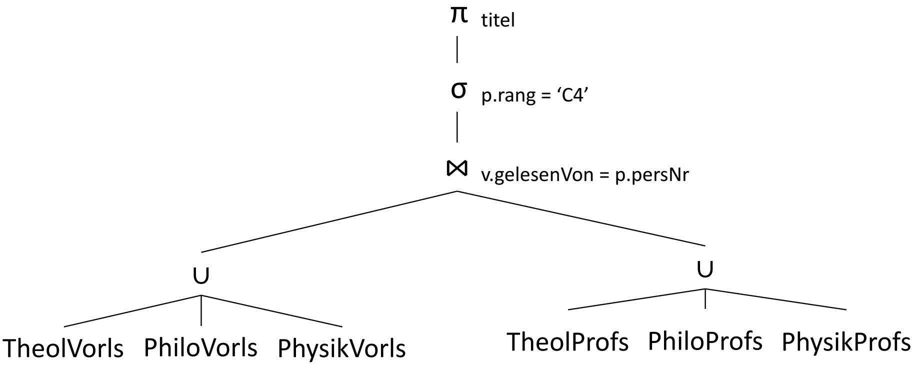
Every machine in the cluster has a chunk of the dataset.

- improved query runtimes (especially if no cross-shard communication is required)
- performance heavily relies on the used interconnect
- can accommodate datasets that exceed the capacity of a machine



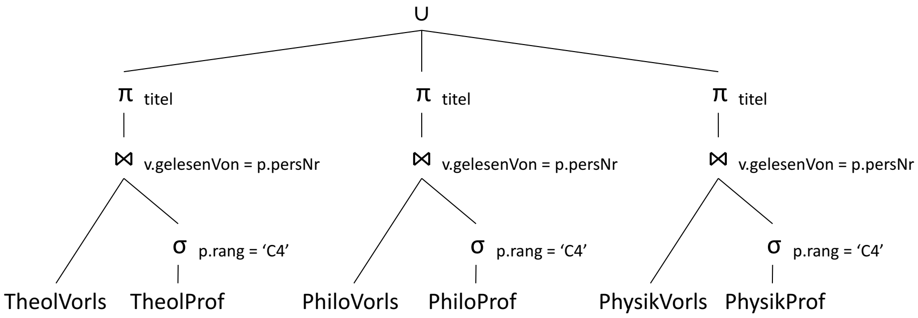
Horizontal Partitioning (Sharding) - Example

```
select Title
from Vorlesungen v, Professoren p
where v.gelesenVon = p.persNr
 and p.rang = 'C4';
```



Horizontal Partitioning (Sharding) - Example (Optimized)

```
select Title
from Vorlesungen v, Professoren p
where v.gelesenVon = p.persNr
 and p.rang = 'C4';
```



Shard Allocation

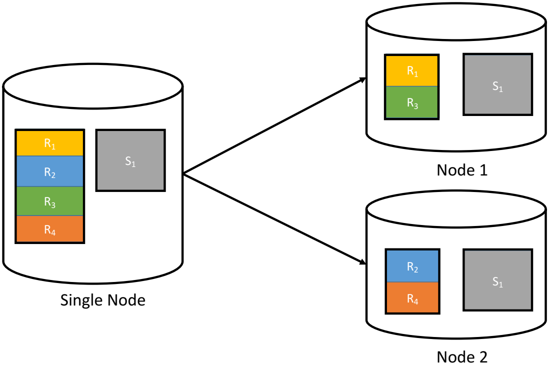
Shards can be allocated to the cluster machines in different ways.

- every machine receives one shard
- every machine receives multiple shards (e.g., MemSQL allocates 8 shards to a leaf node)
- having more shards than machines results in better skew handling

Replication and Sharding

Replication and sharding can be applied together.

- benefits of both are combined
- however, this leads to an increased resource consumption



Joins

Joins in a replicated setting are easy (i.e., not different from local joins). What is more challenging are joins when data is sharded across multiple machines. Join types include:

- co-located joins
- distributed join (involves cross-shard communication)
- broadcast join (involves cross-shard communication)

Co-Located Joins

One option is to shard the tables that need to be joined on the respective join column. That way, joins can be computed locally and the individual machines do not need to communicate with each other.
Eventually, the individual results are send to a master node that combines the results.

Distributed Join

Re-distribute both tables based on the corresponding join columns to eventually compute the join locally.

Broadcast Join

Send smaller relation to all machines to compute the join locally.

Counting the Sum

Let's consider summing up the `quantity` in `lineitem`, again. Assume `lineitem` does not fit into the DRAM of a single machine. Depending on the used interconnect, it turns out that reading `lineitem` from remote machines is faster than reading it from a local SSD.

	bandwidth	query time
FDR InfiniBand	7GB/s	0.1s
10GB ethernet	1.25GB/s	0.6s
1GB ethernet	125MB/s	6s
rotating disk	200MB/s	3.6s
SATA SSD	500MB/s	1.6s
PCIe SSD	2GB/s	0.36s
DRAM	20GB/s	0.04s

Counting the Sum - Sharding

Lower query latencies by sharding the data to multiple nodes.

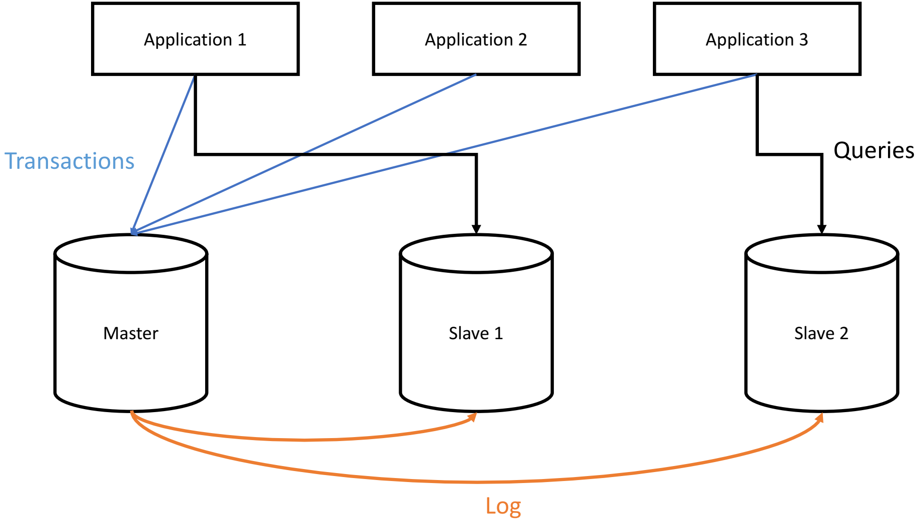
- each node only stores a partition of `lineitem`
- every node sums up its partition of `lineitem`
- a master node sums up the local sums

Vanilla PostgreSQL

What can we do with vanilla PostgreSQL?

- PostgreSQL supports read replicas
  - from version 9.6, these replicas are kept in sync, allowing for consistent reads
  - allows for load-balancing read workloads and thus improved query throughput
- PostgreSQL neither supports data distribution nor distributed queries

Replication in PostgreSQL



Greenplum to the rescue!

Pivotal Greenplum is a distributed open-source database based on PostgreSQL.

- supports data distribution and partitioning
- master and segment (child) nodes
  - master nodes contain the schemas
  - segment nodes contain the data
- additional standby master and secondary (mirror) segment nodes

Greenplum: Distribution/Partitioning Schemes

Distribution/partitioning schemes can be specified when creating a table.

- `DISTRIBUTED BY` specifies how data is spread (sharded) across segments
  - random (round-robin) or hash-based distribution
- `PARTITION BY` specifies how data is partitioned within a segment
  - list of values or range (numeric or date)
  - subpartitioning

Greenplum: Distribution Example[2]

A table with a hash-based distribution:

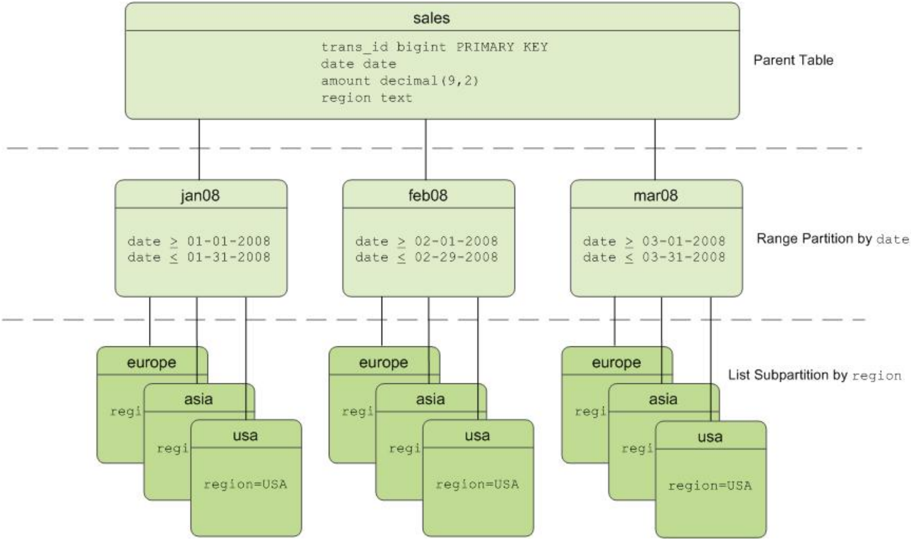
```
CREATE TABLE products
(name varchar(40),
prod_id integer,
supplier_id integer)
DISTRIBUTED BY (prod_id);
```

A table with a random (round-robin) distribution:

```
CREATE TABLE random_stuff
(things text,
doodads text,
etc text)
DISTRIBUTED RANDOMLY;
```

[2] http://gpdb.docs.pivotal.io/4350/admin_guide/ddl/ddl-table.html

Greenplum: Partitioning Example



3

[3] http://gpdb.docs.pivotal.io/4350/admin_guide/ddl/ddl-partition.html

MemSQL

MemSQL is yet another (distributed) database system.

- compatible with MySQL
- data can be sharded across multiple machines
- in addition to sharding, tables can be replicated to all machines (reference tables) allowing for broadcast joins
- also supports distributed and co-located joins

MemSQL

A MemSQL cluster consists of aggregator and leaf nodes.

- aggregator nodes handle metadata, distribute queries, and aggregate results
- aggregator nodes are also responsible for cluster monitoring and failover
- leaf nodes act as the storage layer of the cluster and execute SQL queries

MemSQL

By default, MemSQL shards tables by their primary key. A manual shard key can be specified as follows:

```
CREATE TABLE clicks (
click_id BIGINT AUTO_INCREMENT,
user_id INT,
page_id INT,
ts TIMESTAMP,
SHARD KEY (user_id),
PRIMARY KEY (click_id, user_id)
); 4
```

[4] https://docs.memsql.com/docs/distributed-sql

Conclusion

- a distributed system provides access to a bunch of machines and makes them look like a single one to the user
- these systems naturally have more resources (e.g., compute power, storage) than a single machine
- this makes clusters attractive for developers to simply put any data there
- **BUT**: the synchronization of these resources may be expensive