Finally, let us put things into perspective by looking at alternatives to MapReduce.

We start with Dryad from Microsoft.

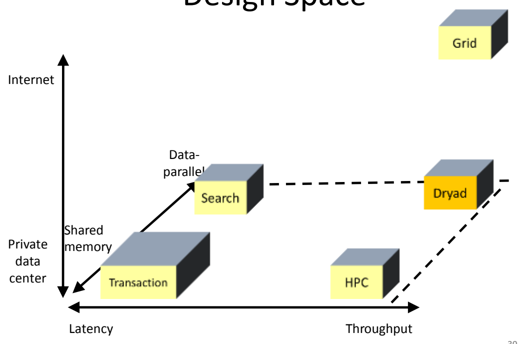
Overview

- Michael Isard, Mihai Budiu, Yuan Yu, Andrew Birrell, and Dennis Fetterly. Dryad: distributed data-parallel programs from sequential building blocks. European Conference on Computer Systems (EuroSys), Lisbon, Portugal, March 21-23, 2007
- Yuan Yu, Michael Isard, Dennis Fetterly, Mihai Budiu, Ulfar Erlingsson, Pradeep Kumar Gunda, and Jon Currey. DryadLINQ: A System for General-Purpose Distributed Data-Parallel Computing Using a High-Level Language. Symposium on Operating System Design and Implementation (OSDI), San Diego, CA, December 8-10, 2008
- Presentation based on authors' slides

Outline

- Dryad Design
- Implementation
- Policies as Plug-ins
- Building on Dryad

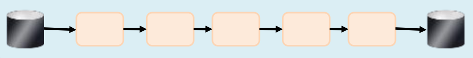
Design Space



2-D Piping

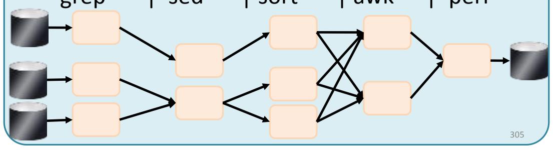
- Unix Pipes: 1-D

  grep | sed | sort | awk | perl

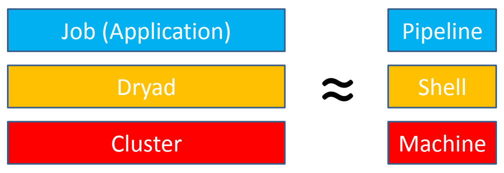


- Dryad: 2-D

  grep^{1000} | sed^{500} | sort^{1000} | awk^{500} | perl^{50}



Dryad = Execution Layer



Outline

- Dryad Design
- Implementation
- Policies as Plug-ins
- Building on Dryad

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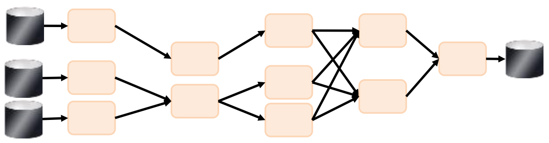
Virtualized 2-D Pipelines



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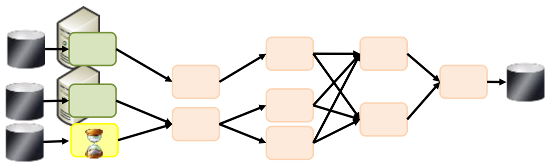
Virtualized 2-D Pipelines



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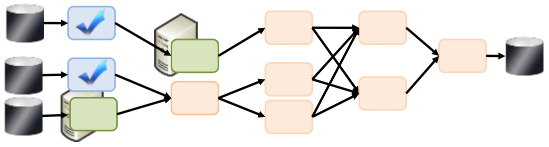
Virtualized 2-D Pipelines



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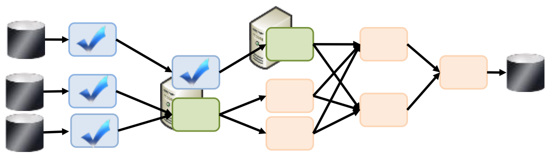
Virtualized 2-D Pipelines



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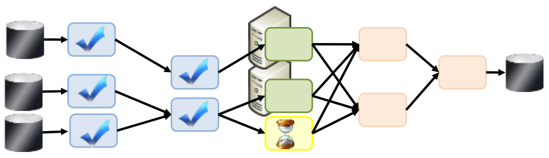
Virtualized 2-D Pipelines

- 2D DAG
- multi-machine
- virtualized



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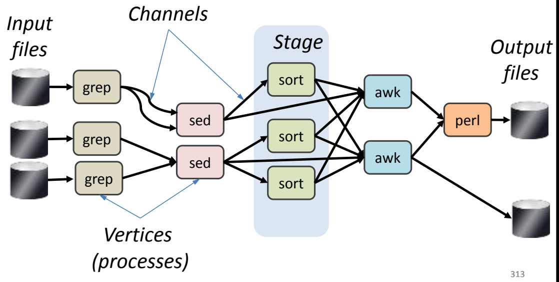
Dryad Job Structure

grep^{1000} | sed^{500} | sort^{1000} | awk^{500} | perl^{50}



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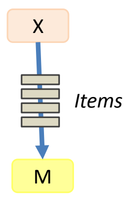
Channels



Finite Streams of items

- distributed filesystem files (persistent)
- SMB/NTFS files (temporary)
- TCP pipes (inter-machine)
- memory FIFOs (intra-machine)

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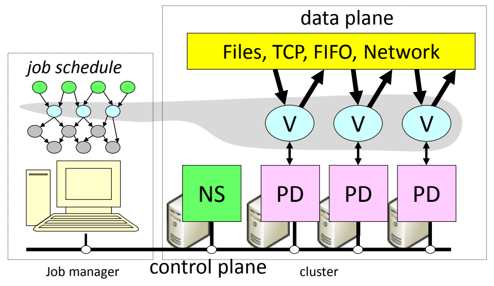
Architecture



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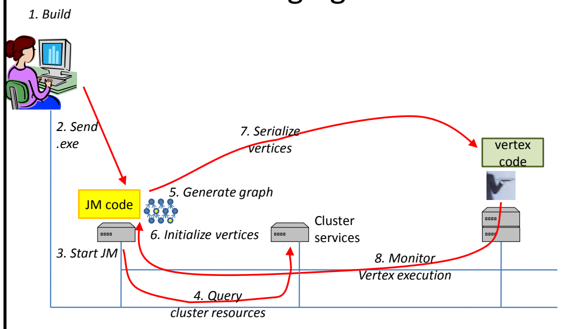
Staging



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Outline

- Dryad Design
- Implementation
- Policies and Resource Management
- Building on Dryad

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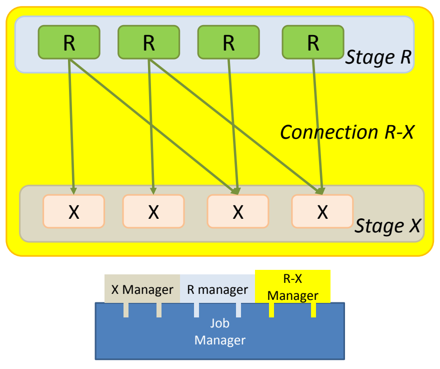
Policy Managers



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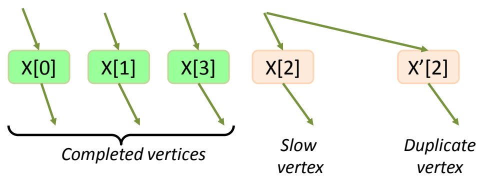
Duplicate Execution Manager



Duplication Policy = f(running times, data volumes)

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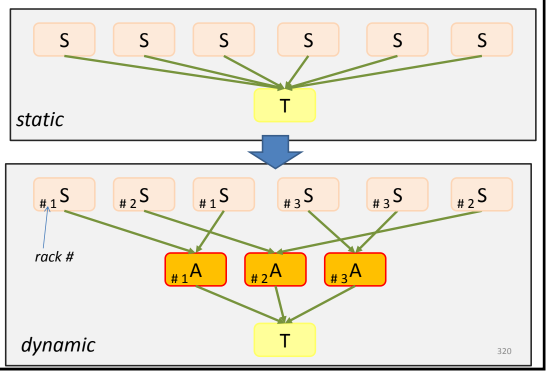
Aggregation Manager



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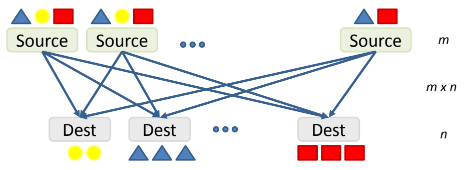
Data Distribution (Group By)



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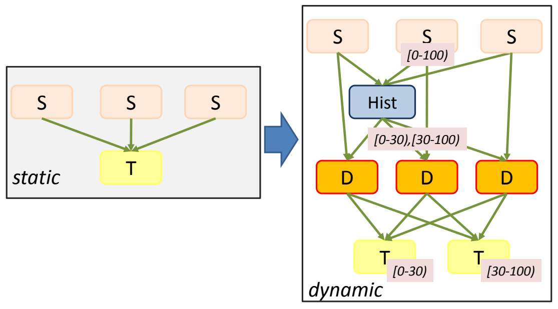
Range-Distribution Manager



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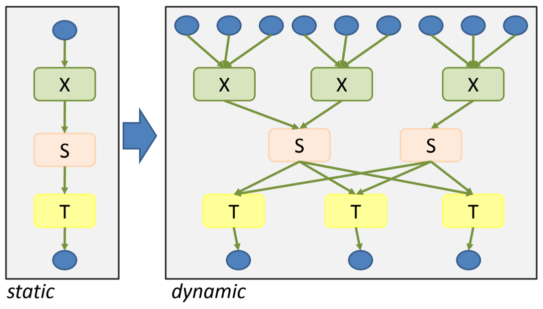
Goal: Declarative Programming



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Outline

- Dryad Design
- Implementation
- Policies as Plug-ins
- Building on Dryad

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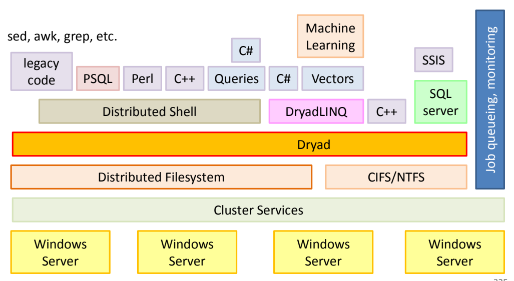
Software Stack

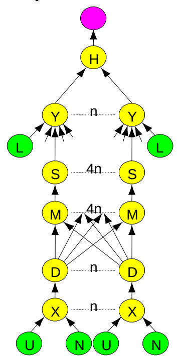


Example Query: Sky Server

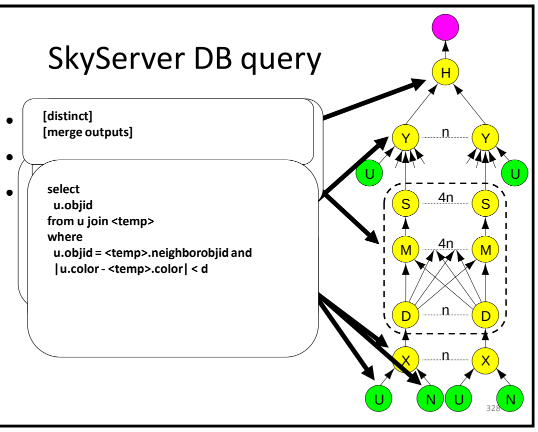
- Table photoPrimary
  - All identified astronomical objects (354,254,163 records)
  - ID, color magnitude in 5 bands (u, g, r, i, z)
- Table neighbors
  - For each object, neighbors within 30 arc seconds (2,803,165,372 records)
- Query 18: gravitational lens effect
  - Find all objects that have neighbors whose color is similar to that object

SkyServer Query 18

```
select distinct U.ObjID
into results
  from photoPrimary U,
        neighbors N,
        photoPrimary L
where U.ObjID = N.ObjID
  and U.mode = 1
  and L.ObjID = N.NeighborObjID
  and U.ObjID < L.ObjID
  and abs((U.u-U.g)-(L.u-L.g))<0.05
  and abs((U.g-U.r)-(L.g-L.r))<0.05
  and abs((U.r-U.i)-(L.r-L.i))<0.05
  and abs((U.i-U.z)-(L.i-L.z))<0.05
```



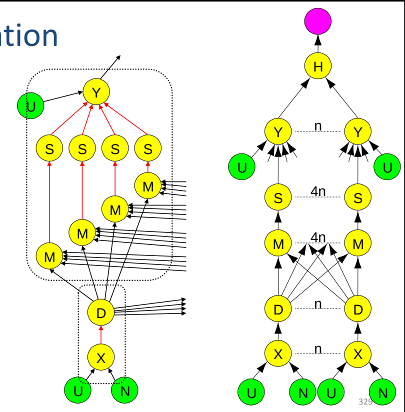
SkyServer DB query



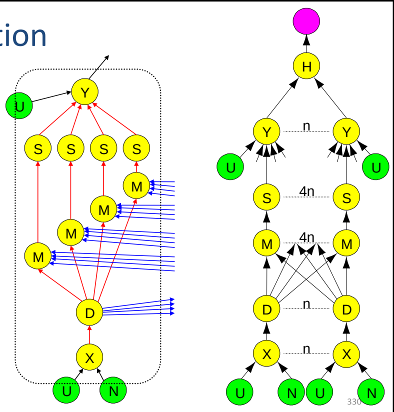
```
[distinct]
[merge outputs]
```

```
select
  u.objid
from u join <temp>
where
  u.objid = <temp>.neighborobjid and
  |u.color - <temp>.color| < d
```

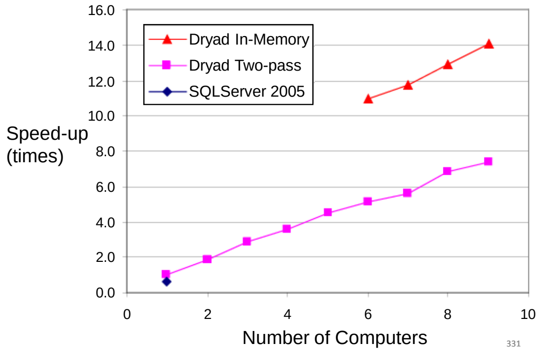
Optimization



Optimization



SkyServer Q18 Performance



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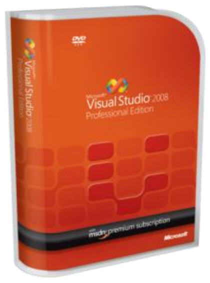
DryadLINQ

- Declarative programming
- Integration with Visual Studio
- Integration with .Net
- Type safety
- Automatic serialization
- Job graph optimizations
  - static
  - dynamic
- Conciseness



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LINQ

```
Collection<T> collection;
bool IsLegal(Key);
string Hash(Key);

var results = from c in collection
              where IsLegal(c.key)
              select new { Hash(c.key), c.value};
```

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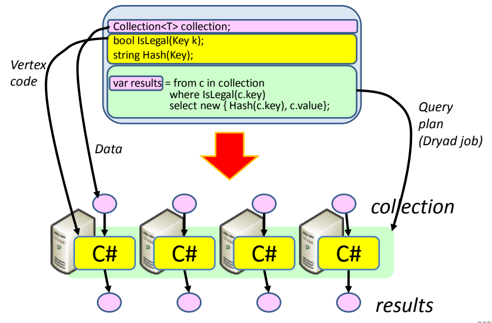
DryadLINQ = LINQ + Dryad



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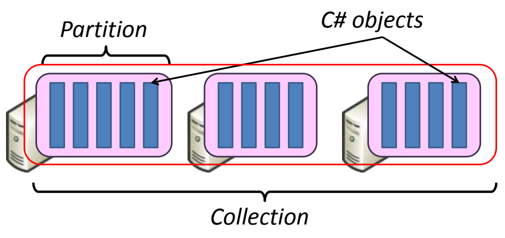
Data Model



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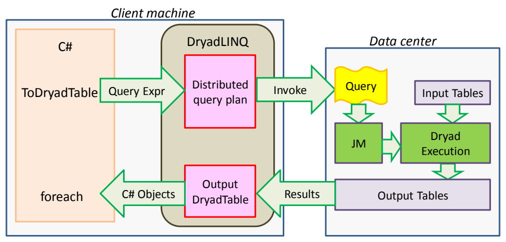
Query Providers



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Example: Histogram

```
public static IQueryable<Pair> Histogram(
    IQueryable<LineRecord> input, int k)
{
   var words = input.SelectMany(x => x.line.Split(' '));
   var groups = words.GroupBy(x => x);
   var counts = groups.Select(x => new Pair(x.Key, x.Count()));
   var ordered = counts.OrderByDescending(x => x.count);
   var top = ordered.Take(k);
   return top;
}
```

"A line of words of wisdom"
["A", "line", "of", "words", "of", "wisdom"]
[["A"], ["line"], ["of", "of"], ["words"], ["wisdom"]]
[{"A", 1}, {"line", 1}, {"of", 2}, {"words", 1}, {"wisdom", 1}]
[{"of", 2}, {"A", 1}, {"line", 1}, {"words", 1}, {"wisdom", 1}]
[{"of", 2}, {"A", 1}, {"line", 1}]

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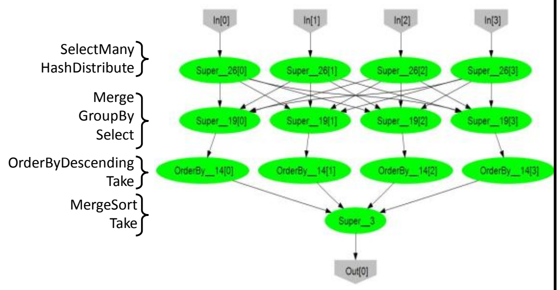
Histogram Plan



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Map-Reduce in DryadLINQ

```
public static IQueryable<S> MapReduce<T,M,K,S>(
    this IQueryable<T> input,
    Expression<Func<T, IEnumerable<M>>> mapper,
    Expression<Func<M,K>> keySelector,
    Expression<Func<IGrouping<K,M>,S>> reducer)
{
    var map = input.SelectMany(mapper);
    var group = map.GroupBy(keySelector);
    var result = group.Select(reducer);
    return result;
}
```

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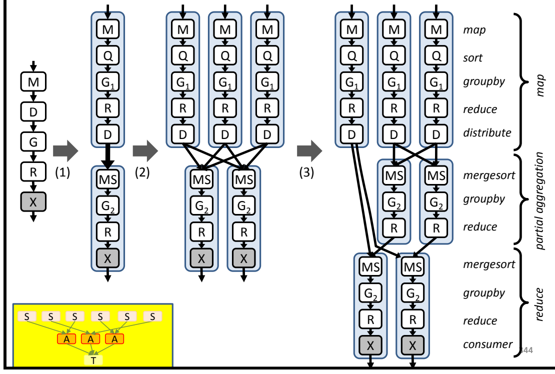
Map-Reduce Plan



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Distributed Sorting in DryadLINQ

```
public static IQueryable<TSource>
DSort<TSource, TKey>(this IQueryable<TSource> source,
                        Expression<Func<TSource, TKey>> keySelector,
                        int pcount)
{
        var samples = source.Apply(x => Sampling(x));
        var keys = samples.Apply(x => ComputeKeys(x, pcount));
        var parts = source.RangePartition(keySelector, keys);
        return parts.OrderBy(keySelector);
}
```

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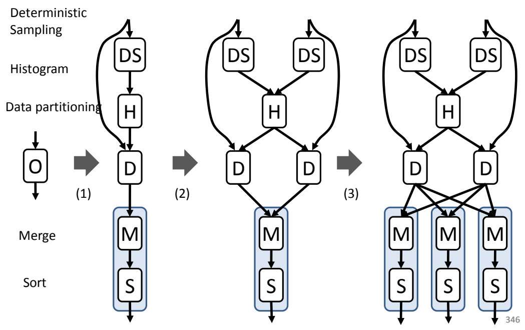
Distributed Sorting Plan



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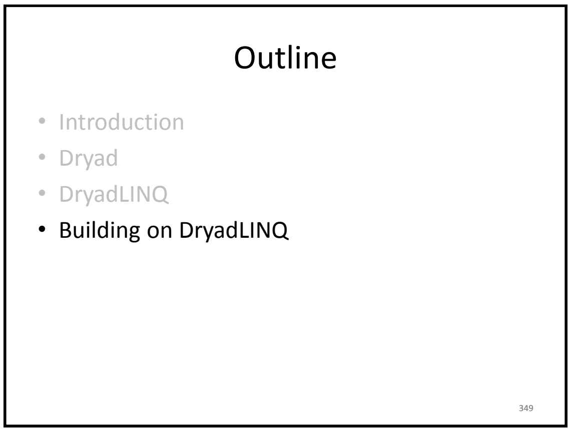

Outline

- Introduction
- Dryad
- DryadLINQ
- Building on DryadLINQ

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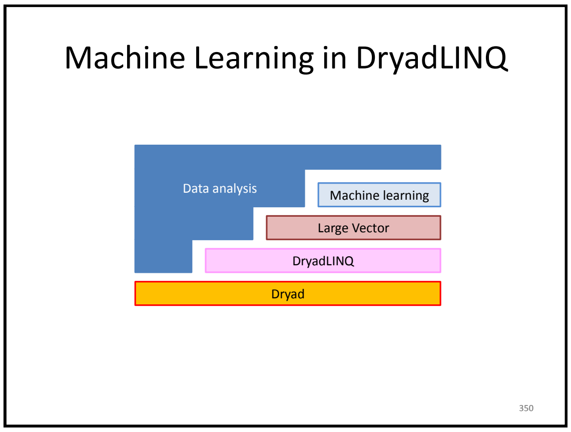

Machine Learning in DryadLINQ

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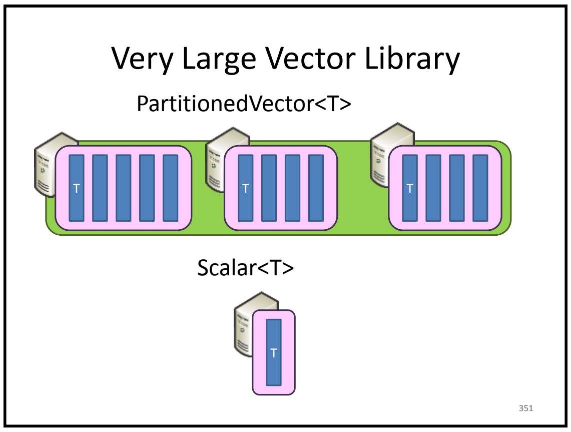

Very Large Vector Library

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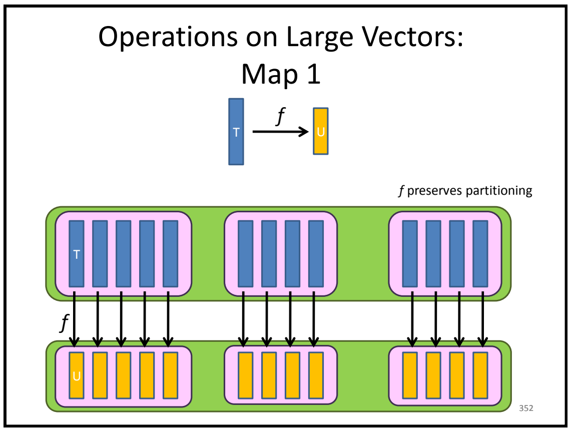

Operations on Large Vectors: Map 1

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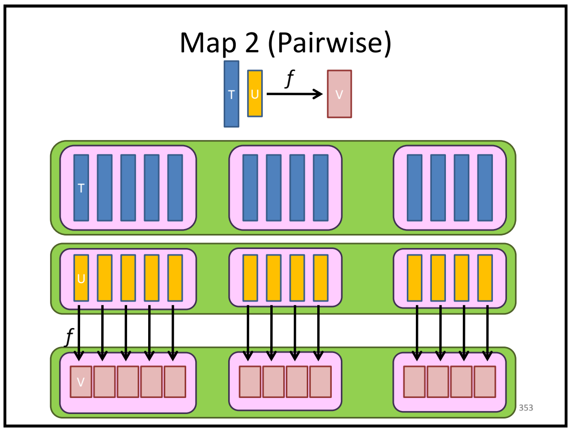

Map 2 (Pairwise)

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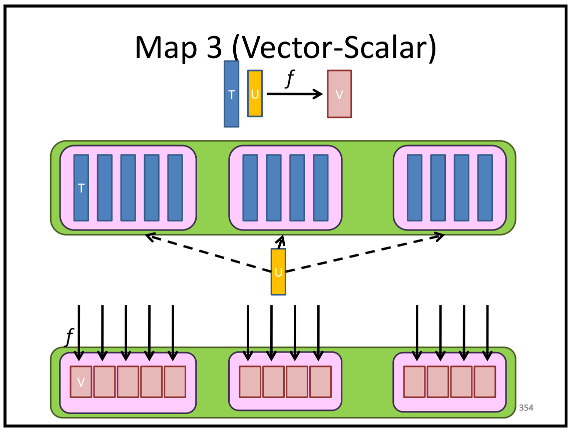

Map 3 (Vector-Scalar)

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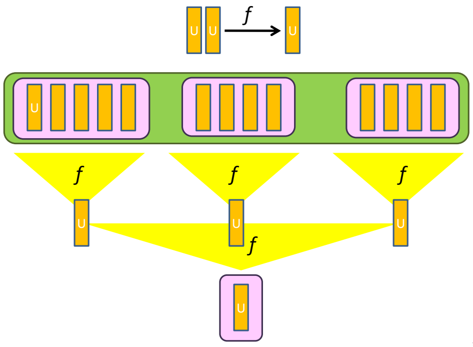
Reduce (Fold)



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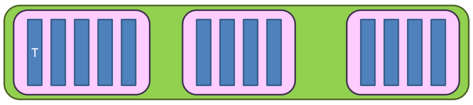
Linear Algebra



$$\{T, U, V\} = \{\Re, \Re^m, \Re^{m\times n}\}$$

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Linear Regression

- Data

$$x_t \in \Re^n, y_t \in \Re^m \qquad t \in \{1,\dots,n\}$$

- Find

$$A \in \Re^{n\times m}$$

- S.t.

$$Ax_t \approx y_t$$

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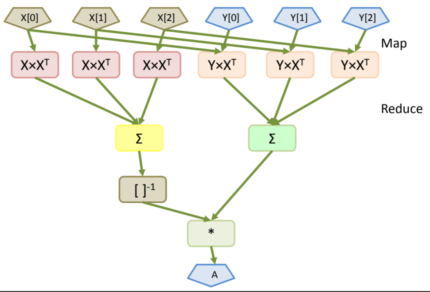
Analytic Solution

$$A = (\sum_t y_t \times x_t^T)(\sum_t x_t \times x_t^T)^{-1}$$



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Linear Regression Code

$$A = (\sum_t y_t \times x_t^T)(\sum_t x_t \times x_t^T)^{-1}$$

```
Vectors x = input(0), y  = input(1);
Matrices xx = x.PairwiseOuterProduct(x);
OneMatrix xxs = xx.Sum();
Matrices yx = y.PairwiseOuterProduct(x);
OneMatrix yxs = yx.Sum();
OneMatrix xxinv = xxs.Map(a => a.Inverse());
OneMatrix A = yxs.Map(
       xxinv, (a, b) => a.Multiply(b));
```

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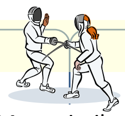
Dryad   Map-Reduce



- Many similarities

Dryad	Map-Reduce
• Execution layer	• Exe + app. model
• Job = arbitrary DAG	• Map+sort+reduce
• Plug-in policies	• Few policies
• Program=graph gen.	• Program=map+reduce
• Complex (⬆features)	• Simple
• New (< 2 years)	• Mature (> 4 years)
• Still growing	• Widely deployed
• Internal	• Hadoop

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Conclusions

- Dryad = distributed execution environment
- Application-independent (semantics oblivious)
- Supports rich software ecosystem
  - Relational algebra
  - Map-reduce
  - LINQ
  - Etc.
- DryadLINQ = A Dryad provider for LINQ
- This is only the beginning!

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Finally, let us put things into perspective by looking at alternatives to MapReduce.

We started with Dryad from Microsoft, now move on to parallel and distributed databases.

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Parallel Database Systems

- Data: relations
- Relational operators process relations and output relations
  - Selection
  - Projection
  - Join
  - Group By and aggregation
- Query language: SQL

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SQL

- Declarative language
  - Specify what you want, not how to get it
- Database optimizer chooses best implementation
  - Query plan: DAG of operators and their implementations
  - Minimize cost of query plan
    - I/O cost, CPU cost
  - Optimizer explores space of query plans, chooses best one

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SQL in Parallel

- Same query, just replace optimizer
  - Take data location and network cost into account
  - Optimize for latency or total cost
- Add new operators
  - Exchange operator: behaves like an iterator, but receives input via inter-process communication rather than iterator procedure calls
  - Split and Merge: create and join parallel dataflows
- Add new operator implementations
  - Semi-join implementation to reduce network communication cost
- The optimizer is more complex, but SQL does not need to change

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Distributed Query Optimization

- Start: calculus query on global relations
- Transform into algebraic query on global relations
- Perform data localization, using fragment schema, to generate algebraic query on fragments
- Perform global optimization to create distributed query execution plan
- Run on local sites in parallel

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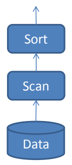
Pipeline Parallelism

- Computation of one operator proceeds in parallel with another
- Model: output pulls from last operators, which pulls from its inputs and so on



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Limited Benefits of Pipeline Parallelism

- Relational pipelines are usually not very long
  – Ten or longer is rare
- Some operators are blocking and cannot be pipelined
  – Aggregates, sorting
- Execution cost of one operator might be much larger than the others
  – Limits speedup obtained by pipelining

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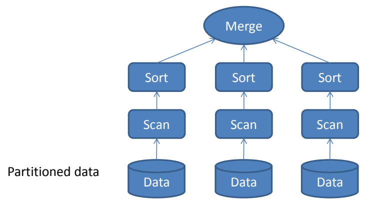
Partitioned Parallelism

- Query performs batch-style computation on many input tuples



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Data Partitioning

- Round-robin
  – Simple, but not helpful for associative access
- Hash partitioning
  – Assign tuples to partition using hash function
  – Good for associative access (equality-based)
  – Not good for range queries
- Range partitioning
  – Partition data into continuous ranges
  – Good for range queries, parallel sort
  – Risks data skew (uneven partitions) and execution skew (uneven access pattern)

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Distributed Transactions?

- Transactions were crucial for the success of database systems
- Enable concurrent processing of multiple queries, but programmers could write them as if they executed in isolation

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The ACID Properties

- Atomicity: Either all or none of the transaction's actions are executed
  – Even when a crash occurs mid-way
- Consistency: Transaction run by itself must preserve consistency of the database
  – User's responsibility
- Isolation: Transaction semantics do not depend on other concurrently executed transactions
- Durability: Effects of successfully committed transactions should persist, even when crashes occur

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Example

```
T1:     BEGIN  A=A+100,  B=B-100  END
T2:     BEGIN  A=1.06*A,  B=1.06*B  END
```

- T1 transfers $100 from B's account to A's account.
- T2 credits both accounts with a 6% interest payment.
- There is no guarantee that T1 will execute before T2 or vice-versa, if both are submitted together.
- However, the net effect must be equivalent to these two transactions running serially in some order.

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Example (Contd.)

- Consider a possible interleaving (schedule):

```
T1:     A=A+100,                B=B-100
T2:                 A=1.06*A,               B=1.06*B
```

- This is OK. But what about:

```
T1:     A=A+100,                            B=B-100
T2:                 A=1.06*A, B=1.06*B
```

- The DBMS's view of the second schedule:

```
T1:     R(A), W(A),                                  R(B), W(B)
T2:                     R(A), W(A), R(B), W(B)
```

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Scheduling Transactions

- Serial schedule: Schedule that does not interleave the actions of different transactions.
  - Easy for programmer, easy to achieve consistency
  - Bad for performance
- Equivalent schedules: For any database state, the effect (on the objects in the database) of executing the first schedule is identical to the effect of executing the second schedule.
- Serializable schedule: A schedule that is equivalent to some serial execution of the transactions.
  - Retains advantages of serial schedule, but addresses performance issue

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Anomalies with Interleaved Execution

```
T1:     R(A), W(A),                 R(B), W(B), Abort
T2:                 R(A), W(A), C
```

- Reading Uncommitted Data (WR Conflicts, "dirty reads")
- Example: T1(A=A-100), T2(A=1.06A), T2(B=1.06B), C(T2), T1(B=B+100)
- T2 reads value A written by T1 before T1 completed its changes
- If T1 later aborts, T2 worked with invalid data

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More Anomalies

```
T1:     R(A),                          R(A), W(A), C
T2:             R(A), W(A), C
```

- Unrepeatable Reads (RW Conflicts)
- T1 sees two different values of A, even though it did not change A between the reads
- Example: online bookstore
  - Only one copy of a book left
  - Both T1 and T2 see that 1 copy is left, then try to order
  - T1 gets an error message when trying to order
  - Could not have happened with serial execution

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Even More Anomalies

```
T1:     W(A),                 W(B), C
T2:             W(A), W(B), C
```

- Overwriting Uncommitted Data (WW Conflicts)
- T1's B and T2's A persist, which would not happen with any serial execution
- Example: 2 people with same salary
  - T1 sets both salaries to 2000, T2 sets both to 1000
  - Above schedule results in A=1000, B=2000, which is inconsistent

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Aborted Transactions

- All actions of aborted transactions have to be undone
- Dirty read can result in unrecoverable schedule
  - T1 writes A, then T2 reads A and makes modifications based on A's value
  - T2 commits, and later T1 is aborted
  - T2 worked with invalid data and hence has to be aborted as well; but T2 already committed…
- Recoverable schedule: cannot allow T2 to commit until T1 has committed
  - Can lead to cascading aborts

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Preventing Anomalies through Locking

- DBMS can support concurrent transactions while preventing anomalies by using a locking protocol
- If a transaction wants to read an object, it first requests a shared lock (S-lock) on the object
- If a transaction wants to modify an object, it first requests an exclusive lock (X-lock) on the object
- Multiple transactions can hold a shared lock on an object
- At most one transaction can hold an exclusive lock on an object

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Lock-Based Concurrency Control

- Strict Two-phase Locking (Strict 2PL) Protocol:
  - Each Xact must obtain the appropriate lock before accessing an object.
  - All locks held by a transaction are released when the transaction is completed.
  - All this happens automatically inside the DBMS
- Strict 2PL allows only serializable schedules.
  - Prevents all the anomalies shown earlier

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Deadlocks

- Assume T1 and T2 both want to read and write objects A and B
  - T1 acquires X-lock on A; T2 acquires X-lock on B
  - Now T1 wants to update B, but has to wait for T2 to release its lock on B
  - But T2 wants to read A and also waits for T1 to release its lock on A
  - Strict 2PL does not allow either to release its locks before the transaction completed. Deadlock!
- DBMS can detect this
  - Automatically breaks deadlock by aborting one of the involved transactions

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Performance of Locking

- Locks force transactions to wait
- Abort, restart due to deadlock wastes work
- Waiting for locks becomes worse as more transactions execute concurrently
  - Allowing more concurrent transactions at some point leads to thrashing
  - Need to limit max number of concurrent transactions to prevent thrashing
  - Minimize lock contention by reducing the time a Xact holds locks

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Distributed Transactions

- Transactions take longer to access remote objects
  - Need to hold locks longer
  - Greater probability for waiting and deadlocks
- What if the network partitions?
  - Transaction cannot acquire/release some locks
- Even without partitions, the problem is hard
  - Need to coordinate commit between multiple nodes
  - What happens if some participating node crashes?
- Standard protocol: 2PC (2-phase commit)

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2PC Basics

- Commit-request phase
  - Coordinator asks all participants to prepare for commit
  - Participants vote YES or NO to commit request
- Commit phase
  - Based on participants' votes, coordinator decides to commit (if all voted YES) or abort
  - Coordinator notifies participants about decision
  - Participants apply corresponding action (commit or abort) locally

2PC Problems

- 2PC = blocking protocol
  - Nodes cannot make a decision without hearing from coordinator, e.g., might hold on to locks forever if coordinator is down and they answered YES to first request
- Expensive for many-worker transactions
- Some issues were addressed by later 2PC modifications, but the basic problems remain