Cluster-Based Algorithms for Relational Join

The New Computation Model

More Efficient Joins Via Replication

Optimum Strategies for Special Cases

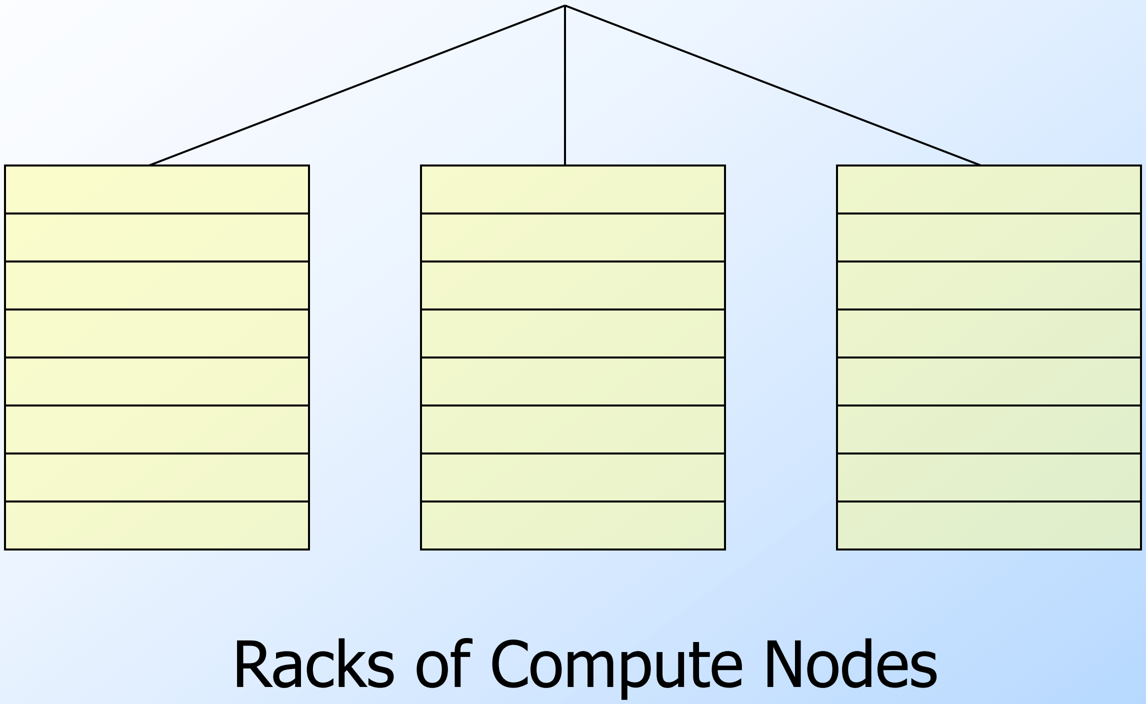
Joint work with Foto Afrati

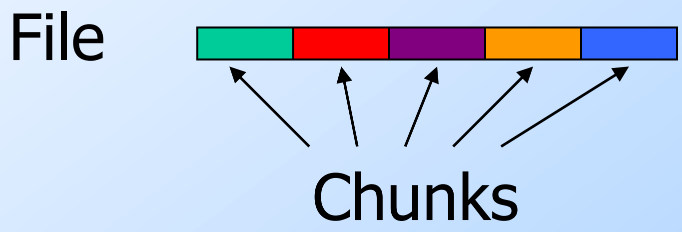
Next-Generation File Systems

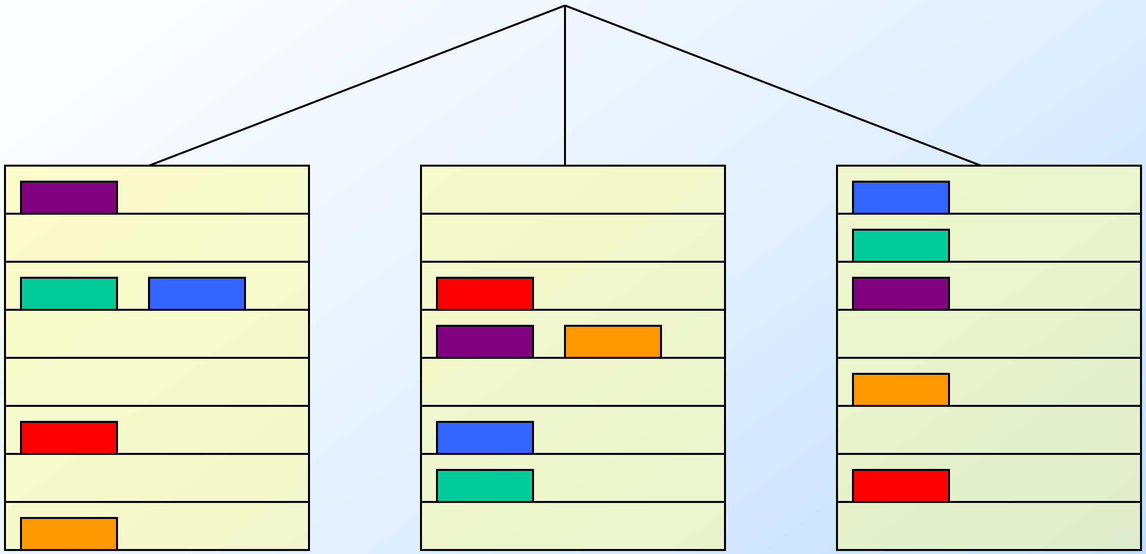
- Files are very large.
- They are divided into *chunks*.
  - Perhaps 16MB to a chunk.
- Chunks are replicated at several *compute-nodes*.
- A *master* (possibly replicated) keeps track of all locations of all chunks.

Compute Nodes

- Organized into racks.
- Intra-rack connection typically gigabit speed.
- Inter-rack connection faster by a small factor.


Racks of Compute Nodes


File
Chunks



3-way replication of files, with copies on different racks.

Implementations

- *GFS* (Google File System – proprietary).
- *HDFS* (Hadoop Distributed File System – open source).
- *KFS* (Kosmix File System).
- *Clustera* (Implementation at U. Wisconsin).

Moving Up the Computation Stack

- *BigTable* (Google retrieval system for objects).
- *Hadoop* (Open-source implementation of Google's map-reduce).
- *PIG* (Yahoo! implementation of relational algebra/SQL on top of Hadoop).

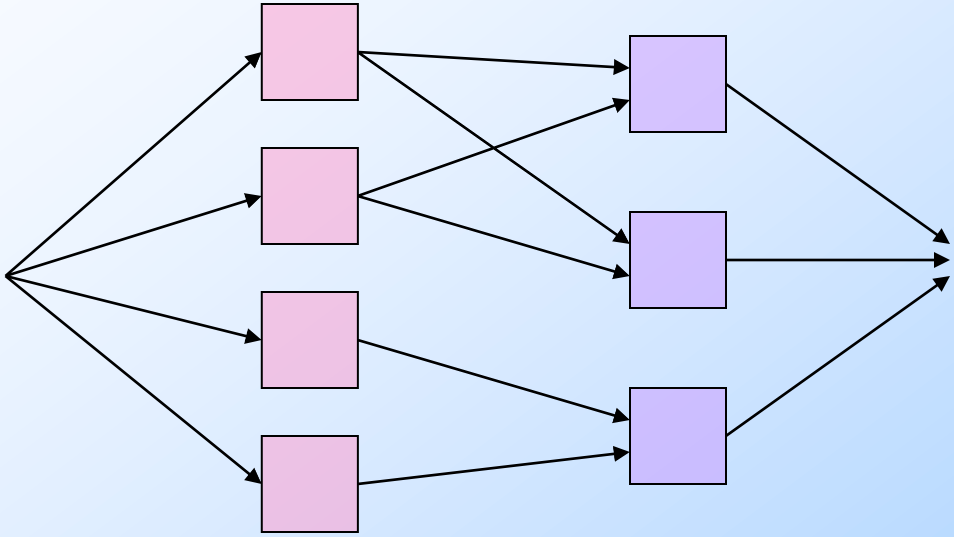
Reading and Writing Files

- Order of elements in a file doesn't matter.
  - Example: A file could be a collection of documents; order within a doc matters, but not the order of docs.
- Parallel reading, writing OK.

Algorithms

- *Algorithm* = acyclic collection of processes.
  - Arc means the process at the tail feeds some data to the head.

Example Algorithm



Communication Cost

- *Communication cost* = sum of sizes of inputs to all processes of an algorithm.
- Also, *elapsed* communication cost: the maximum over all paths through the acyclic graph of the sizes of the inputs to each of the processes on that path.

Why Not Count Output Size?

- Outputs of one process are inputs to at least one other, or are algorithm output.
- Algorithm outputs tend to be small because users can't make use of too much information.

Why Not Count Processing Time?

- In the types of applications we discuss, work by a process is usually proportional to input size.
- And it occurs in main memory, so we can do a lot in the time it takes to get your input over a gigabit line.

Natural Join of Relations

- Given: a collection of relations, each with attributes labeling their columns.
- Find: Those tuples over all the attributes such that when restricted to the attributes of any relation R, that tuple is in R.

Example: Natural Join

A	B
0	1
1	2

B	C
1	2
2	3

A	C
1	3
2	1

The join:

A	B	C
1	2	3

Map-Reduce Algorithms

- *Map* processes send inputs to key-value pairs.
  - "keys" are not necessarily unique.
- Outputs of Map processes are sorted by key, and each key is assigned to one *Reduce* process.
- Reduce processes combine values associated with a key.

Joining by Map-Reduce

- Suppose we want to compute R(A,B) JOIN S(B,C), using *k* compute nodes.
- *R* and *S* are each stored in a chunked file.

Joining by Map-Reduce – (2)

- Use a hash function *h* from B-values to *k* buckets.
- Many Map processes take chunks from R and S, and send:
  - Tuple R(a,b) to Reduce process h(b).
  - Tuple S(b,c) to Reduce process h(b).

Joining by Map-Reduce – (3)

- If R(a,b) joins with S(b,c), then both tuples are sent to Reduce process h(b).
- Thus, their join (a,b,c) will be produced there and shipped to the output file.

3-Way Join

- Consider a chain of three relations:

  R(A, B) JOIN S(B, C) JOIN T(C,D)

- Example: R, S, and T are "friends" relations.
- We could join any two by the the 2-way map-reduce algorithm shown, then join the third with the resulting relation.
- But intermediate joins are large.

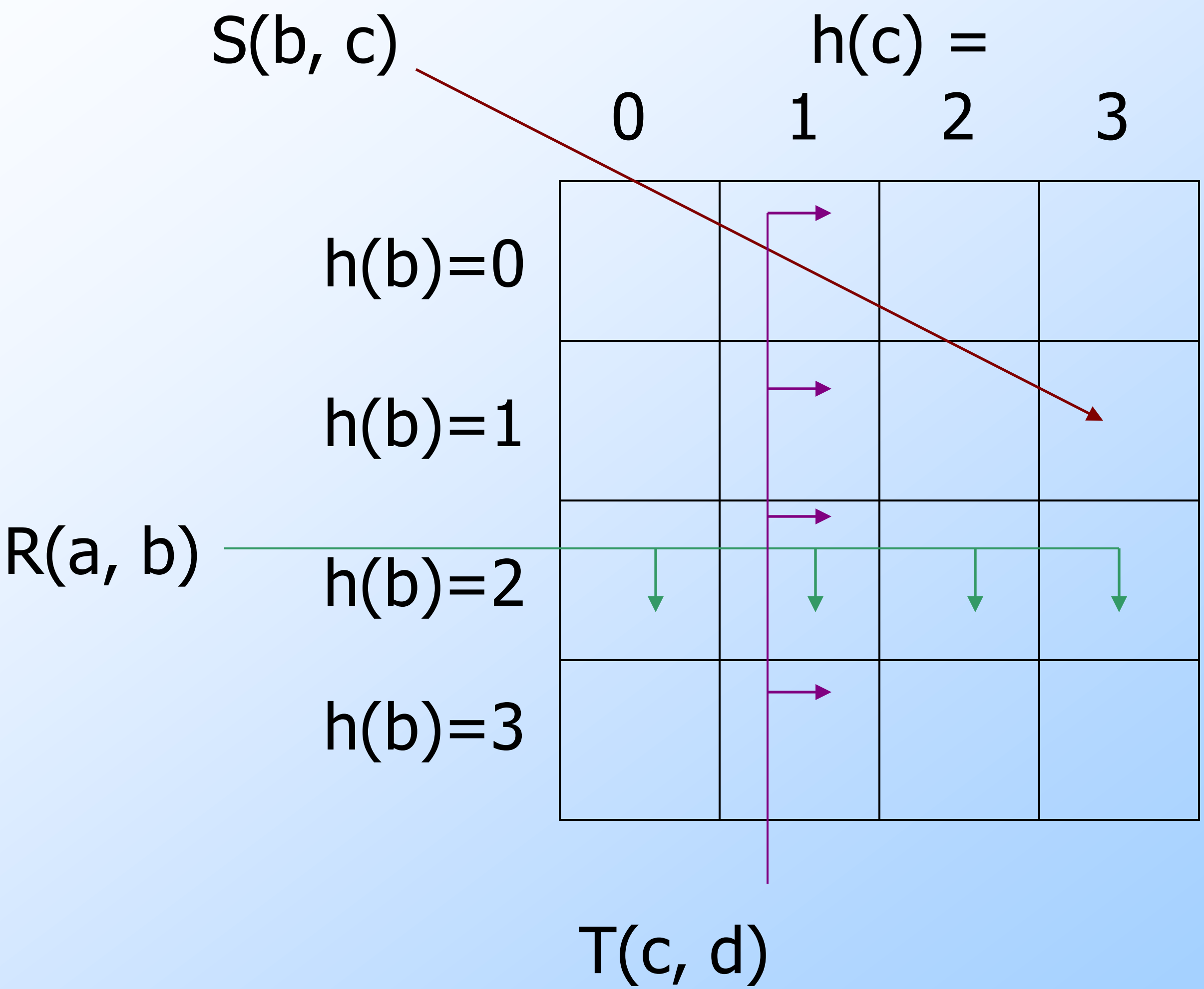
3-Way Join – (2)

- An alternative is to divide the work among $k = m^2$ Reduce processes.
- Hash both B and C to m values.
- A Reduce process corresponds to a hashed B-value and a hashed C-value.

3-Way Join – (3)

- Each S-tuple S(b,c) is sent to one Reduce process: (h(b), h(c)).
- But each tuple R(a,b) must be sent to *m* Reduce processes (h(b), x).
- And each tuple T(c,d) must be sent to *m* Reduce processes (y, h(c)).

Example: m = 4; k = 16.



3-Way Join – (4)

- Thus, any joining tuples R(a,b), S(b,c), and T(c,d) will be joined at the Reduce process (h(b), h(c)).
- Communication cost: s + mr + mt.
  - Convention: Lower-case letter is the size of the relation whose name is the corresponding upper-case letter.
    - Example: *r* is the size of R.

Comparison of Methods

- Suppose for simplicity that:
  - Relations R, S, and T have the same size *r*.
  - The probability of two tuples joining is *p*.
- The 3-way join has cost r(2m+1).
- Two two-way joins have a cost of:
  - 3r to read the relations, plus
  - pr^2 to read the join of the first two.
  - Total = r(3+pr).

Comparison – (2)

- 3-way beats 2-way if $2m+1 < 3+pr$.
- *pr* is the multiplicity of each join.
  - Thus, the 3-way chain-join is useful when the multiplicity is high.
- Example: relations are "friends"; *pr* is about 300. $m^2 = k$ can be 20,000.
- Example: relations are Web links; *pr* is about 15. $m^2 = k$ can be 64.

Some Questions

- When we discussed the 3-way chain-join, we used attributes B and C for the *map-key* (index for the Reduce processes).
- Why not include A and/or D?
- Why use the same number of buckets for B and C?

Share Variables

- For the general problem, we use a *share variable* for each attribute.
  - The number of buckets into which values of that attribute are hashed.
- Convention: The share variable for an attribute is the corresponding lower-case letter.
  - Example: the share variable for attribute A is always *a*.

Share Variables – (2)

- The product of all the share variables is *k*, the number of Reduce processes.
- The communication cost of a multiway join is the sum of the size of each relation times the product of the share variables for the attributes that *do not* appear in the schema of that relation.

Example: Minimizing Cost

- Consider the cyclic join
  R(A, B) JOIN S(B, C) JOIN T(A, C)
- Cost function is rc + sa + tb.
- Construct the Lagrangean:
  $rc + sa + tb - \lambda(abc - k)$
- Take derivative wrt each share variable, then multiply by that variable.
  - Result is 0 at minimum.

Example – Continued

- d/da of rc + sa + tb – λ(abc – k) is s – λbc.
- Multiply by a and set to 0: $sa - \lambda abc = 0$.
- Note: $abc = k$: $sa = \lambda k$.
- Similarly, d/db and d/dc give: $sa = tb = rc = \lambda k$.
- Solution: $a = (krt/s^2)^{1/3}$; $b = (krs/t^2)^{1/3}$; $c = (kst/r^2)^{1/3}$;
- Cost = $rc + sa + tb = 3(krst)^{1/3}$.

Dominated Attributes

- Certain attributes can't be in the map-key.
- A *dominates* B if every relation of the join with B also has A.
- Example:

R(A,B,C) JOIN S(A,B,D) JOIN T(A,E) JOIN U(C,E)

Every place with B

Also has A

Example – (2)

R(A,B,C) JOIN S(A,B,D) JOIN T(A,E) JOIN U(C,E)

- Cost expression:

  rde + sce + tbcd + uabd

- Since *b* appears wherever *a* does, if there were a minimum-cost solution with *b* > 1, we could replace *b* by 1 and *a* by *ab*, and the cost would *lower*.

Dominated Attributes – Continued

- Thus, we do not put any dominated attribute in the map-key.
- This rule explains why, in the discussion of the chain join

R(A, B) JOIN S(B, C) JOIN T(C,D)

we did not put A or D in the map key.

Solving the General Case

- Unfortunately, there are more complex cases than dominated attributes, where the equations derived from the Lagrangean imply a positive sum of several terms = 0.
  - We can fix, generalizing dominated attributes, but we have to branch on which attribute needs to be eliminated from the map-key.

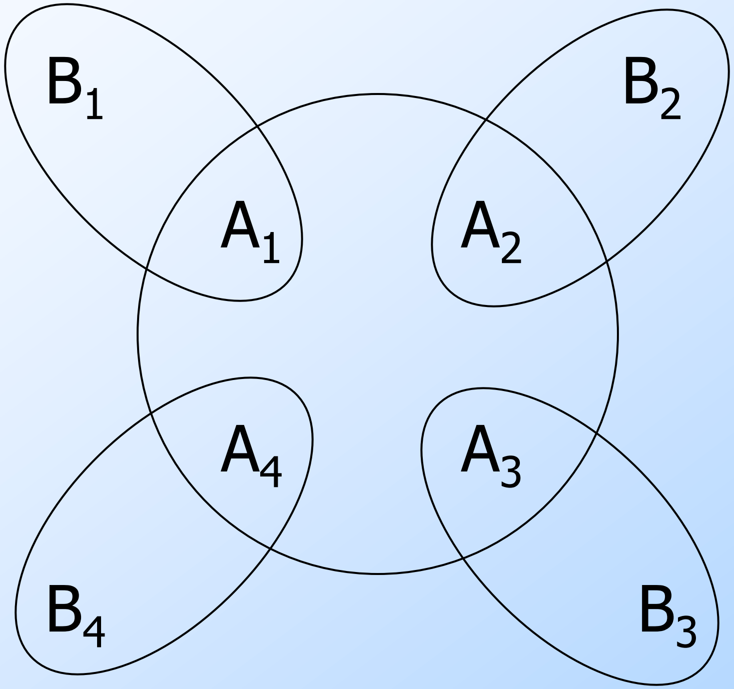
Solving – (2)

- Solutions not in integers:
  - Drop an attribute with a share < 1 from the map-key and re-solve.
  - Round other nonintegers, and treat k as a suggestion, since the product of the integers may not be k.

Special Case: Star Joins

- A *star join* combines a large *fact table* $F(A_1,A_2,\ldots,A_n)$ with tiny *dimension tables* $D_1(A_1,B_1)$, $D_2(A_2,B_2)$,…, $D_n(A_n,B_n)$.
  - There may be other attributes not shown, each belonging to only one relation.
- Example: Facts = sales; dimensions tell about buyer, product, etc.

Star-Join Pattern



Star Joins – (2)

- Map-key = the A's.
  - B's are dominated.
- Solution: $d_i a_i = \lambda k$ for all i.
  - That is, the shares are inversely proportional to the dimension-table sizes.

Cool Application of Star Join Result

- Fact/dimension tables are often used for analytics.
  - Example: fact table is all sales records; dimension tables give info about customers, products, suppliers, etc.
- Aster Data approach: partition fact table among nodes permanently; replicate needed pieces of dimension tables.

Star-Join Application – (2)

- Our solution lets you partition the fact table to *k* nodes.
- Replication of tuples in the dimension tables is minimized.

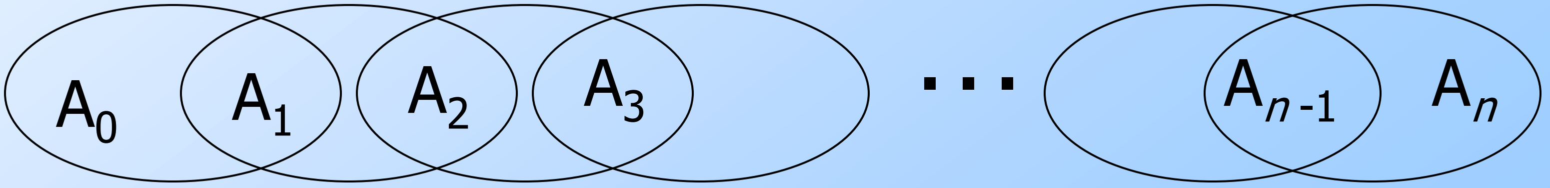
Chain Joins

- A chain join has the form

$R(A_0, A_1)$ JOIN $R(A_1, A_2)$ JOIN … JOIN $R(A_{n-1}, A_n)$

  - Other attributes may appear, but only in one relation.

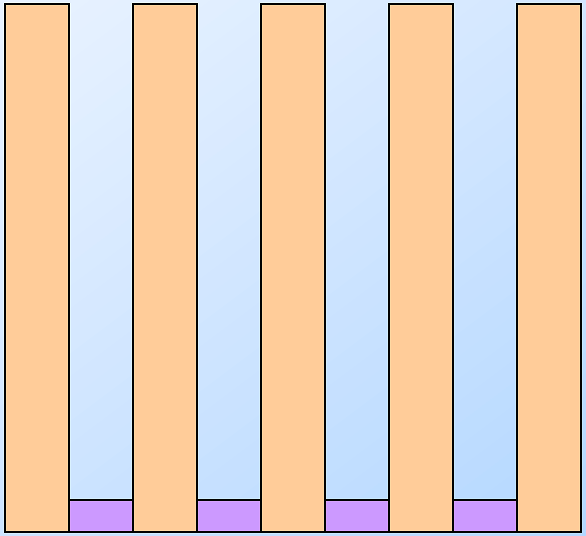
- A_0 and A_n are dominated; other attributes are in the map-key.



Special Case: All Relations Have the Same Size

- Illustrates strange behavior.
  - Even and odd n have very different distributions of the share variables.
- Even n : $a_2 = a_4 = \ldots = a_{n-2} = 1$; $a_1 = a_3 = \ldots = a_{n-1} = k^{2/n}$

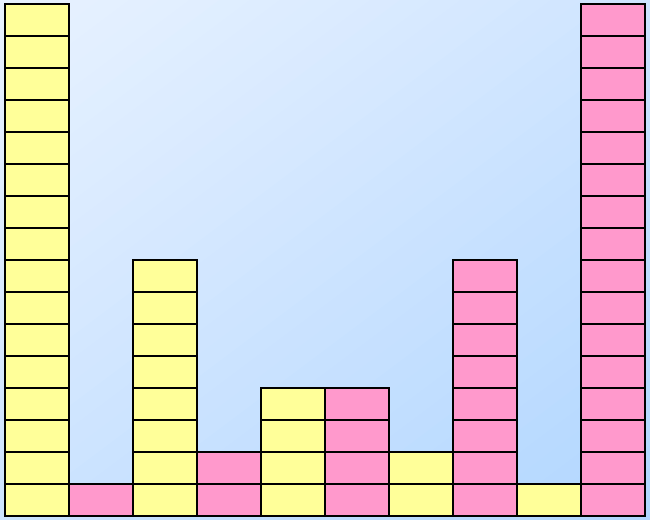
Pattern for Even *n*



Odd *n*, Equal Relation Sizes

- Even a's grow exponentially.
  - That is, $a_4 = a_2^2$; $a_6 = a_2^3$; $a_8 = a_2^4$,…
- The odd a's form the inverse sequence.
  - That is, $a_1 = a_{n-1}$; $a_3 = a_{n-3}$; $a_5 = a_{n-5}$;…

Pattern for Odd *n*



Summary

1. Multiway joins can be computed by replicating tuples and distributing them to many compute nodes.
2. Minimizing communication requires us to solve a nonlinear optimization.
3. Method wins for star queries and queries on high-fanout graphs.
4. Exact solution for chain and star queries.