Lecture 7
Map Reduce III

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Learning Goals Today

- Get to know idea of more general workflow systems
- Get to know some popular examples
- Understand the definition of *communication cost*
- Understand the definition of *wall clock time*
- Get to know theory and intuition of *complexity theory* for MapReduce

Workflow Systems

Workflow Systems: Introduction

- Workflow systems generalize MapReduce
- Just as much as MapReduce:
  - They're built on distributed file systems
  - They orchestrate large numbers of tasks with only small input provided by the user
  - They automatically handle failures
- In addition:
  - Single tasks can do other things than just Map or Reduce
  - Tasks interact in more complex ways

WORKFLOW SYSTEMS: FLOW GRAPH

- A *function* represents arbitrary functionality within a workflow
  - and not just 'Map' or 'Reduce'
- Functions are represented as *nodes* of the *flow graph*
- Arcs $a \rightarrow b$ for two functions a, b mean that the output of function a is provided to function b as input
- *Note:* The same function could be used by many tasks

Workflow Systems

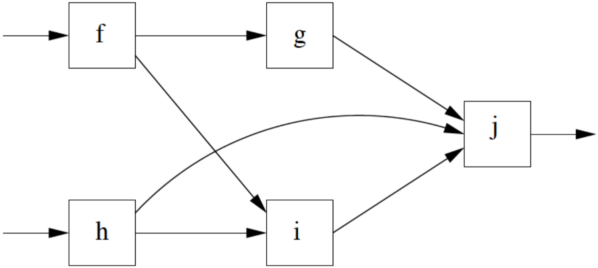


Figure: More complex workflow than MapReduce

Adopted from `mmds.org`

Workflow Systems: Acyclic Flow Graph

- *Cycle:* Path through graph having same start and end node
  - Figure on slide before has no cycles
  - *Acyclic graphs:* Graphs without cycles
- It is easier to deal with *acyclic flow graphs*
  - This means that one cannot return to functions
    ☞ output of functions not part of their own input
  - Facilitates to order tasks in terms of their dependencies
  - So requires less sophistication from workflow system

Workflow Systems: Acyclic Flow Graph

- *Blocking Property:* tasks only generate output upon completion
    - Blocking property easily applicable only in acyclic workflows
    - If input depends on own output, completion of task hard to determine a priori
- *Simple Example of Workflow:* Cascades of Map-Reduce jobs
    - Output of Map jobs generated only after all Map tasks are completed
    - Reduce can work only on complete output anyway

Popular Workflow Systems

- *Spark:* developed by UC Berkeley
- *TensorFlow:* Google's system, primarily developed for neural network computations
- *Pregel:* also by Google, for handling *recursive* (i.e. cyclic) workflows
- *Snakemake:* easy-to-use workflow system, inspired by MakeFile logic/functionality

SPARK

- State-of-the-art workflow system:
  - Very efficient with failures
  - Very efficient in grouping tasks among nodes
  - Very efficient in scheduling execution of functions
- Basic concept: *Resilient Distributed Dataset (RDD)*
  - Generalizes key-value pair: RDD contains objects of one type
  - *Distributed:* broken into chunks held at different nodes
  - *Resilient:* recoverable from losses of (even all) chunks
- *Transformations* (steps of functions) turn RDD into others
- *Actions* turn other data (from surrounding file system) into RDD's and vice versa

SPARK: TRANSFORMATIONS

Remark: For the following, consider equivalent methods in Python

- *Map* takes a function as parameter and applies it to every element of an RDD, generating a new one
    - Turns one object into exactly another object, but not several ones
    - Remember: Map from MapReduce generates several key-value pairs from one object
- *Flatmap* is like Map from MapReduce, and generalizes it from key-value pairs to general object types (not implemented in Python)
- *Filter* takes a predicate as input
    - Predicate is true or false for elements of RDD
    - So RDD is filtered for objects for which predicate applies
    - Yields a 'filtered RDD'

Spark: Reduce and Relational Database Operations

- *Reduce* is an action, and takes as parameter a function that
  - applies to two elements of a particular type T
  - returns one element of type T
  - and is applied repeatedly until a single element remains
  - Works for associative and commutative operations
- Many *Relational Database Operations* are implemented in Spark:
  - Process RDD's reflecting tuples of relations
  - *Examples:* Join, GroupByKey

Spark: Implementation Details

- Spark is similar like MapReduce in handling data (chunks are called *splits*)
- *Lazy evaluation* allows to apply several transformations consecutively to splits:
  - No intermediate formation of entire RDD's
  - Contradicts blocking property, because partial output is passed on to new functions
- *Resilience* (despite lazy evaluation) is maintained by *lineages of RDD's*
- Beneficial trade-off of more complex recovery of failures versus greater speed overall
  - Note that greater speed reduces probability of failures

TensorFlow

- Open-source system developed (initially) by Google for machine-learning applications
- Programming interface for writing sequences of steps
- Data are *tensors*, which are multidimensional matrices
- Power comes from built-in operations applicable to tensors

Recursive Workflows

Examples:

- Calculating fixed-points ($M\bar{v} = \bar{v}$ for a matrix M and v) by iterative application of M to v

$$v \to Mv \to M^2 v \to \ldots \to M^t v \to M^{t+1} v \to \ldots \overset{t\to\infty}{\to} \bar{v} \tag{1}$$

- Gradient descent, e.g. required in TensorFlow for determining optimal sets of parameters for machine learning models
- *Lack of blocking property*:
  - Flow graphs have cycles
  - Tasks may provide their output as input to other tasks whose output in turn results in more input to the first task
  - So generation of output only when task is done does not work
  - *Recovery from failures needs to be reorganized*

TRANSITIVE CLOSURE: DEFINITION

DEFINITION [TRANSITIVE CLOSURE]:
Let $R(X,Y)$ be a relation.

- $R(X,Y)$ is *transitive* if $(x,z) \in R$ and $(z,y) \in R$ imply that $(x,y) \in R$ as well
- The *transitive closure* $\overline{R(X,Y)}$ of $R(X,Y)$ is the *smallest set of tuples to be added* to $R(X,Y)$ that renders the resulting set of tuples transitive

Recursive Workflows: Example

- Directed graph stored as relation $E(X, Y)$, listing arcs from X to Y
- Want to compute relation $P(X, Y)$, listing paths from X to Y
- P is transitive closure of E
- *Reminder:*
  - Natural Join $P(X, Z) \bowtie P(Z, Y)$, for given $x \in X, y \in Y$ generates (x, z, y) for all applicable $z \in Z$, so possibly generates several $(x, z_1, y), (x, z_2, y), \ldots$
  - Project $\pi_{X,Y}$: all $(x, z_1, y), (x, z_2, y), \ldots$ become one (x, y)

Recursive Workflows: Example

- *Reminder:*
  - Natural Join $P(X, Z) \bowtie P(Z, Y)$, for given $x \in X, y \in Y$ generates (x, z, y) for all applicable $z \in Z$, so possibly generates several $(x, z_1, y), (x, z_2, y), \ldots$
  - Project $\pi_{X,Y}$: all $(x, z_1, y), (x, z_2, y), \ldots$ become one (x, y)
- *Algorithm:*
  - *Start:* $P(X, Y) = E(X, Y)$
  - *Iteration:* Add to P tuples

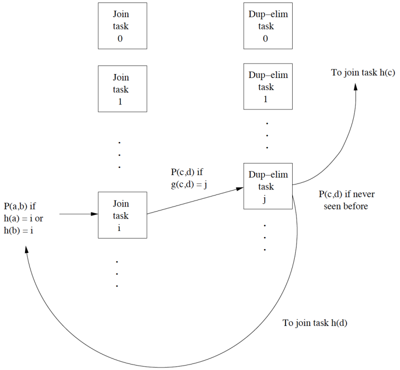
$$\pi_{X,Y}(P(X, Z) \bowtie P(Z, Y)) \tag{2}$$

as pairs of nodes X and Y s.t. for some node Z there is path from X to Z and from Z to Y

Example: Transitive Closure

$P(a, b)$ corresponds to (a, b)

- n Join tasks, corresponding to buckets of hash function h
- Tuple $P(a, b)$ is assigned to Join tasks $h(a)$ and $h(b)$
- i-th Join task receives $P(a, b)$
  - Store $P(a, b)$ locally
  - If $h(a) = i$ look for tuples $P(x, a)$ and produce $P(x, b)$
  - If $h(b) = i$ look for tuples $P(b, y)$ and produce $P(a, y)$



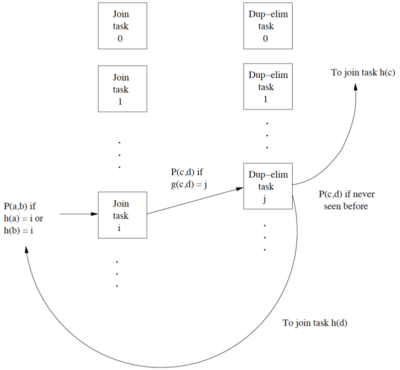
Transitive closure by recursive tasks

Adopted from `mmds.org`

Example: Transitive Closure

$P(a, b)$ corresponds to (a, b)

- *i-th Join task receives $P(a, b)$*
  - Store $P(a, b)$ locally
  - If $h(a) = i$ look for tuples $P(x, a)$ and produce $P(x, b)$
  - If $h(b) = i$ look for tuples $P(b, y)$ and produce $P(a, y)$
- *Additional explanation:*
  - $h(a) = i$, so (a, b) and (x, a) get stored at Join task $i \Rightarrow$ Generate (x, b)
  - $h(b) = i$, so (a, b) and (b, y) get stored at Join task $i \Rightarrow$ Generate (a, y)

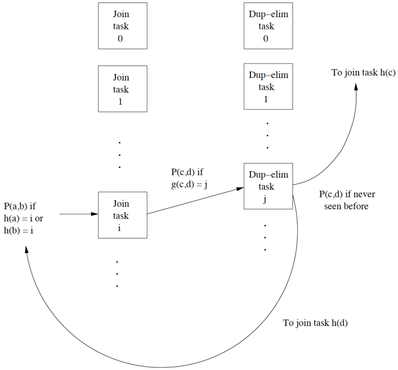


Transitive closure by recursive tasks

Adopted from `mmds.org`

Recursive Workflows: Example

- m Dup-elim tasks, corresponding to buckets of hash function g
- $P(c, d)$ (as output of Join task) is sent to Dup-elim task $j = g(c, d)$
- Dup-elim task j checks whether $P(c, d)$ was received before
  - If *yes*, $P(c, d)$ is ignored (and not stored)
  - If *not*, $P(c, d)$ is stored locally,
  - *and* sent to Join tasks $h(c)$ and $h(d)$

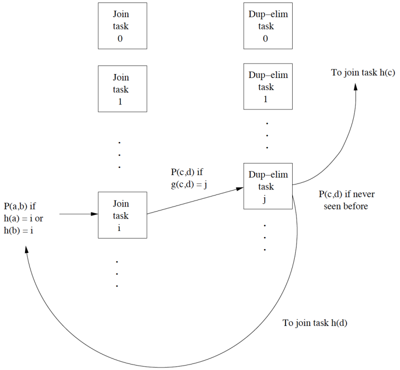


Transitive closure by recursive tasks

Adopted from `mmds.org`

Recursive Workflows: Example

- Every Join task has m output files
- Every Dup-elim task has n output files
- Initially, tuples $E(a, b)$ are sent to Dup-elim tasks $g(a, b)$



Transitive closure by recursive tasks

Adopted from `mmds.org`

Recursive Workflows: Failure Handling

- *Iterated MapReduce:* Application is repeated execution / sequence of MapReduce job(s) (“HaLoop”)
- *Spark Approach:* Lazy evaluation, lineage mechanisms, option to store intermediate results
- *Bulk Synchronous Systems:* Graph-based model using “periodic checkpointing”

Bulk Synchronous Systems: Pregel

- System views data as *graph*:
  - *Nodes* (roughly) reflect tasks
  - *Arcs:* from nodes whose output (messages) are input to other nodes
- *Supersteps:*
  - All messages received by any of the nodes from the previous superstep are processed
  - All messages generated are sent to their destinations
- *Advantage:* Sending messages means communication costs, bundling them reduces costs
- *Failure Management:* Checkpointing entire computation by making copy after each superstep
- May be beneficial to checkpoint periodically after number of supersteps

Snakemake

- Create *reproducible* and *scalable* data analyses
- Workflows described in human readable, Python based language
- Seamlessly scale to server, cluster, grid and cloud environments
- Integrating descriptions of required software, deployable to any execution environment

The Communication-Cost Model

COMMUNICATION COST

Situation

- Algorithm implemented by acyclic network of tasks:
    - Map tasks feeding Reduce tasks
    - Cascade of several MapReduce jobs
    - More general workflow structure (e.g. Fig. 1)

DEFINITION [COMMUNICATION COST]:

- The *communication cost of a task* is the size of the input it receives
- The *communication cost of an algorithm* is the sum of the communication costs of its tasks

Communication Cost

Why Communication Cost?

- Computing communication cost is the way to measure the complexity of distributed algorithm
- Neglect time necessary for tasks to execute
- Importance of communication cost:
  - Tasks tend to be simple (often linear in size of input)
  - Interconnect speed of compute cluster (typically 1 Gbit/sec) slow compared with speed at which processors execute instructions
  - Often there is competition for the interconnect when several nodes are communicating
  - Moving data from disk to memory may exceed runtime

Why not Output Size?

- Output often is input to another task anyway
- Output rarely large in comparison with input or intermediate data

Reminder: Natural Join

Natural Join: $R(A, B) \bowtie S(B, C)$

- **Map:** For each tuple $t = (a, b)$ from R, generate key-value pair $(b, (R, a))$. For each tuple (b, c) from S, generate $(b, (S, c))$.
- **Reduce:** After grouping, each key b has list of values being either of the form (R, a) or (S, c)
  - Construct all possible triples $(b, (R, a), (S, c))$ reflecting all possible combinations of values (R, a) and (S, c)
  - Turn each $(b, (R, a), (S, c))$ into (a, b, c) as output

Communication Cost: Natural Join Example

Joining $R(A,B) \bowtie S(B,C)$ where size of $R = s$ and size of $S = s$.

- *Map:* Chunks of files R, S are input to Map tasks
  ☞ communication cost of Map is $r + s$ (mostly disk to memory)
- *Reduce:* Input to Reduce tasks are $r + s$ many key-value pairs generated by Map ☞ communication cost for Reduce is $O(r + s)$
- *Output of Reduce* could be up to $O(rs)$, so much larger than $O(r + s)$, depending on number of tuples per key b

COMMUNICATION COST $R(A, B) \bowtie S(B, C)$ I

Let sizes of relations R and S be r and s.

Map

- Each chunk of the files holding R and S is fed to one task
  ☞ Communication cost is $r + s$
- Nodes hold chunks already from file distribution step: no internode communication, only disk-to-memory costs
- All Map tasks perform a simple transformation, so only negligible computation cost
- Output about as large as input

Communication Cost $R(A,B) \bowtie S(B,C)$ II

Let sizes of relations R and S be r and s.

Reduce

- Receives and divides input into tuples from R and S
- For each key, pairs each tuple from R with the ones from S
- Output size can vary: can be larger or smaller than $O(r+s)$
  - Many different B-values: output is small
  - Few B-values: output much larger
- Output large: computation cost exceeds $O(r+s)$
- Often output is subsequently aggregated at further nodes
  ☞ Communication cost greater than computation cost

Wall-Clock Time

Definition [Wall-Clock Time]:

The *wall-clock time* is defined to be the time for the entire parallel algorithm to finish.

Example: Careless reasoning could make one assign all tasks to one node, which minimizes communication cost. But the wall-clock time is (likely to be) at its maximum.

EXAMPLE: MULTIWAY JOIN

Consider computing $R(A, B) \bowtie S(B, C) \bowtie T(C, D)$. For simplicity, let us assume that

- the probability that an R- and and S-tuple agree on B
- the probability that an S- and a T-tuple agree on C

are equal. Let p be that probability.

Joining R and S first:

- Communication cost is $O(r + s)$ (see before)
- Size of output is prs
- Hence joining $R \bowtie S$ with T is $O((r + s) + (t + prs))$

Joining S and T first:

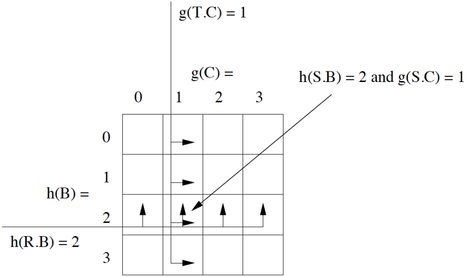
- yields $O((s + t) + (r + pst))$ by analogous considerations

$R(A,B) \bowtie S(B,C) \bowtie T(C,D)$ IN ONE MAPREDUCE

Let p be the probability that an R- and an S-tuple agree on B, matching the probability for an S- and a T-tuple to agree on C.

- Hash B- and C-values, using functions h and g
- Let b and c be the number of buckets for h and g
- Let k be the number of Reducers; require that $bc = k$
  - Each reducer corresponds to a pair of buckets
  - Reducer corresponding to bucket pair (i,j) joins tuples $R(u,v), S(v,w), T(w,x)$ whenever $h(v) = i, g(w) = j$
- Hence Map tasks send R- and T-tuples to more than one reducer
  - R-tuples $R(u,v)$ go to all reducers $(h(v), y), y = 1, ..., c$
    ☞ goes to c reducers
  - T-tuples $T(w,x)$ go to all reducers $(z, g(w)), z = 1, ..., b$
    ☞ goes to b reducers

Multiway Join: One MapReduce II



Sixteen reducers for a 3-way join

Adopted from `mmds.org`

- $h(v) = 2, g(w) = 1$ [in Figure: $v = R.B, w = S.C$]
- S-tuple $S(v, w)$ goes to reducer for key $(2, 1)$
- R-tuple $R(u, v)$ goes to reducers for keys $(2, 0), \ldots, (2, 3)$
- T-tuple $T(w, x)$ goes to reducers for keys $(0, 1), \ldots, (3, 1)$

Multiway Join: One MapReduce III

Communication cost:

- Moving tuples to proper reducers is sum of
  - s to send tuples $S(v, w)$ to $(h(v), g(w))$
  - rc to send tuples $R(u, v)$ to $(h(v), y)$ for each of the c possible $g(w) = y$
  - bt to send tuples $T(w, x)$ to $(z, g(w))$ for each of the b possible $h(b) = z$
- Additional (constant) cost $r + s + t$ to make each tuple input to one of the Map tasks (constant)

Multiway Join: One MapReduce III

Communication cost:

- *Goal:* Select b and c, subject to $bc = k$, to minimize $s + cr + bt$
- Using Lagrangian multiplier λ makes solving for
  - $r - \lambda b = 0$
  - $t - \lambda c = 0$
- It follows that $rt = \lambda^2 bc$, that is $rt = \lambda^2 k$, yielding further $\lambda = \sqrt{\frac{rt}{k}}$
- So, minimum communication cost at $c = \sqrt{\frac{kt}{r}}$ and $b = \sqrt{\frac{kr}{t}}$
- Substituting into $s + cr + bt$ yields $s + 2\sqrt{krt}$
- Adding $r + s + t$ yields $r + 2s + t + 2\sqrt{krt}$, which is usually dominated by $2\sqrt{krt}$

Materials / Outlook

- See *Mining of Massive Datasets*, chapter 2.4–2.5
- For deepening your understanding, voluntary *homework*: please read through 2.6.7
- As usual, see `http://www.mmds.org/` in general for further resources
- Next lecture: “MapReduce / Workflow Systems III; Mining Data Streams I”
  - See *Mining of Massive Datasets* 2.6; 4.1–4.7

Example / Illustration