COMP 322: Fundamentals of Parallel Programming

Lecture 7: Memoization and Map/Reduce

Mack Joyner and Zoran Budimlić
{mjoyner, zoran}@rice.edu

http://comp322.rice.edu

Worksheet #6 solution: Associativity and Commutativity

Recap:

A binary function f is *associative* if f(f(x,y),z) = f(x,f(y,z)).
A binary function f is *commutative* if f(x,y) = f(y,x).

Worksheet problems:

1) Claim: a Finish Accumulator (FA) can only be used with operators that are *associative and commutative.* Why? What can go wrong with accumulators if the operator is non-associative or non-commutative?
You may get different answers in different executions if the operator is non-associative or non-commutative e.g., an accumulator can be implemented using one "partial accumulator" per processor core.

2) For each of the following functions, indicate if it is associative and/or commutative.
a) f(x,y) = x+y, for integers x, y, is associative and commutative
b) g(x,y) = (x+y)/2, for integers x, y, is commutative but not associative
c) h(s1,s2) = concat(s1, s2) for strings s1, s2, e.g., h("ab","cd") = "abcd", is associative but not commutative

Background: Functional Programming

- Eliminate side-effects
  - emphasizes functions whose results that depend only on their inputs and not on any other program state
  - calling a function, f(x), twice with the same value for the argument x will produce the same result both times

Helpful Link: http://en.wikipedia.org/wiki/Functional_programming

Example: Binomial Coefficient

- The coefficient of the x^k term in the polynomial expansion of the binomial power $(1 + x)^n$
- Number of sets of k items that can be chosen from n items
- Indexed by *n* and *k*
  - written as C(n, k)
  - read as "n choose k"
- Factorial Formula: C(n, k) = $\left(\dfrac{n!}{k!(n-k)!}\right)$
- Recursive Formula

  C(n, k) = C(n – 1, k – 1) + C(n – 1, k)

  Base cases: C(n, n) = C(n, 0) = C(0, k) = 1

Helpful Link: http://en.wikipedia.org/wiki/Binomial_coefficient

Example: Binomial Coefficient (Recursive Sequential version)

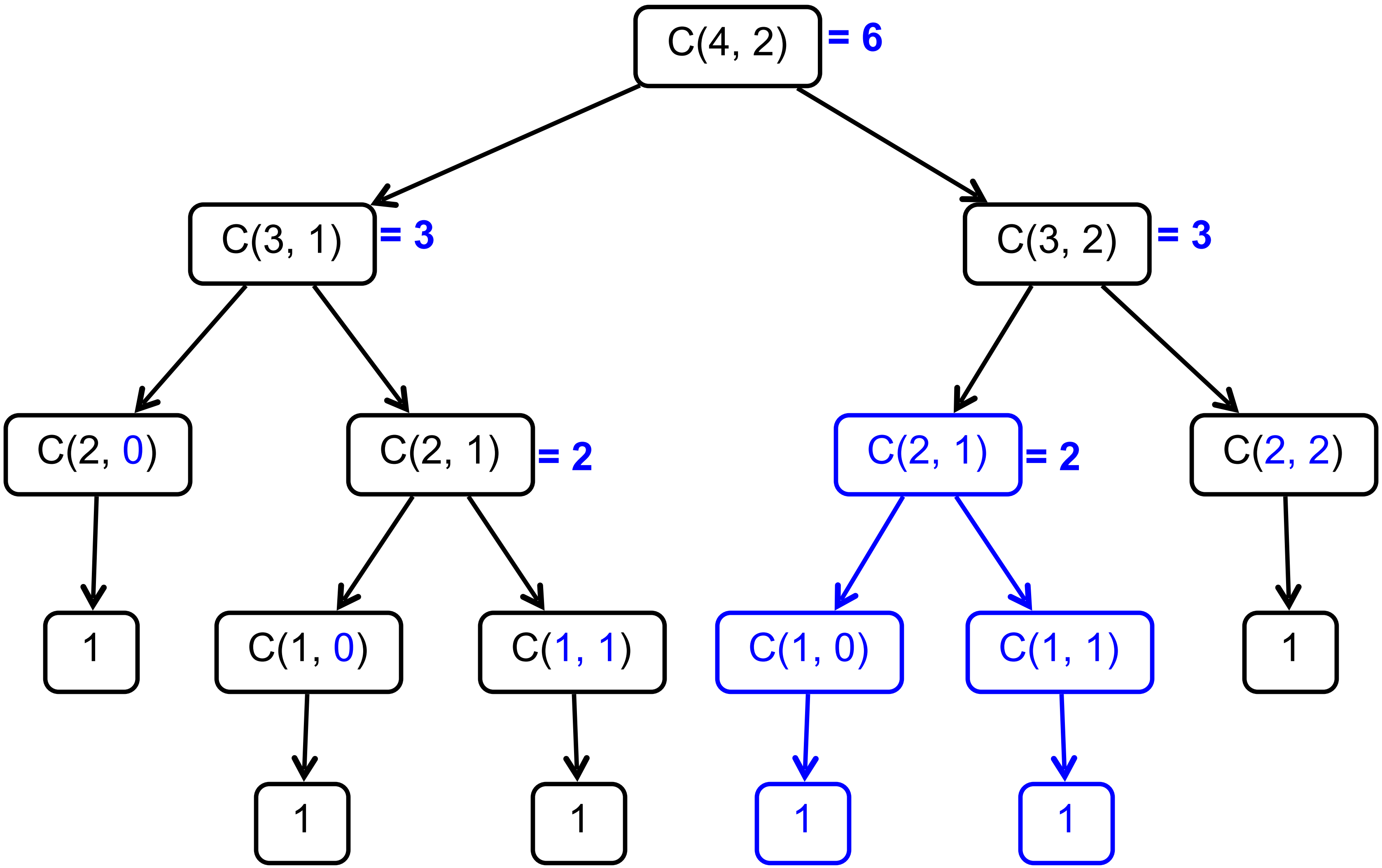
```
int choose(int N, int K) {
    if (N == 0 || K == 0 || N == K) {
        return 1;
    }
    int left  = choose (N-1, K - 1);
    int right = choose (N-1, K);
    return left + right;
}
```

Example: Binomial Coefficient (Parallel Recursive Pseudocode)

```
Integer choose(int N, int K) {
    if (N == 0 || K == 0 || N == K) {
        return 1;
    }
    future<Integer> left =
            future { return choose (N-1, K-1); }
    future<Integer> right =
            future { return choose (N-1, K); }
    return left.get() + right.get();
}
```

- Use of futures supports incremental parallelization with low developer effort

What inefficiencies do you see in the recursive Binomial Coefficient algorithm?



Memoization

- Memoization - saving and reusing previously computed values of a function rather than recomputing them
  - A optimization technique with space-time tradeoff
- A function can only be memoized if it is *referentially transparent*, i.e. functional
- Related to caching
  - memoized function "remembers" the results corresponding to some set of specific inputs
  - memoized function populates its cache of results transparently on the fly, as needed, rather than in advance

Helpful Link: http://en.wikipedia.org/wiki/Memoization

Example: Binomial Coefficient (sequential memoized version)

```
final Map<Pair<Int, Int>, Int> cache = new ...;

int choose(int N, int K) {
    Pair<Int, Int> key = Pair.factory(N, K);
    if (cache.contains(key)) {
        return cache.get(key);
    }
    if (N == 0 || K == 0 || N == K) {
        return 1;
    }
    int left  = choose (N - 1, K - 1);
    int right = choose (N - 1, K);
    int result = left + right;
    cache.put(key, result);
    return result;
}
```

Example: Binomial Coefficient (parallel memoized version w/ futures)

```
final Map<Pair<Int, Int>, future<Integer>> cache = new ...;
Integer choose(final int N, final int K) {
    final Pair<Int, Int> key = Pair.factory(N, K);
    if (cache.contains(key)) {
        return cache.get(key).get();
    }
    future<Integer> f = future {
      if (N == 0 || K == 0 || N == K) return 1;
      future<Integer> left = future { return choose (N-1, K-1); }
      future<Integer> right = future { return choose (N-1, K); }
      return left.get() + right.get();
    }
    cache.put(key, f);
    return f.get();
}
```

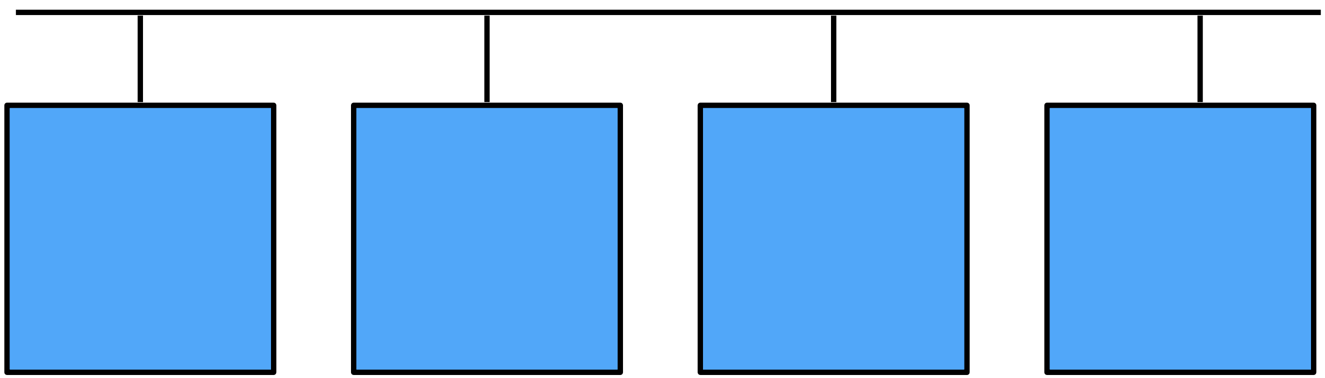
- Assumes availability of a “thread-safe” cache library, e.g., ConcurrentHashMap

Map/Reduce: Streaming data requirements have skyrocketed

- AT&T processes roughly 30 petabytes per day through its telecommunications network
- Google processed roughly 24 petabytes per day in 2009
- Facebook, Amazon, Twitter, etc, have comparable throughputs
- Two Sigma maintains over 100 teraflops of private computing power, continuously computing over 11 petabytes of quantitative data
- In comparison, the IBM Watson knowledge base stored roughly 4 terabytes of data when winning at Jeopardy

Parallelism enables processing of big data

- Continuously streaming data needs to be processed at least as fast as it is accumulated, or we will never catch up
- The bottleneck in processing very large data sets is dominated by the speed of disk access
- More processors accessing more disks enables faster processing



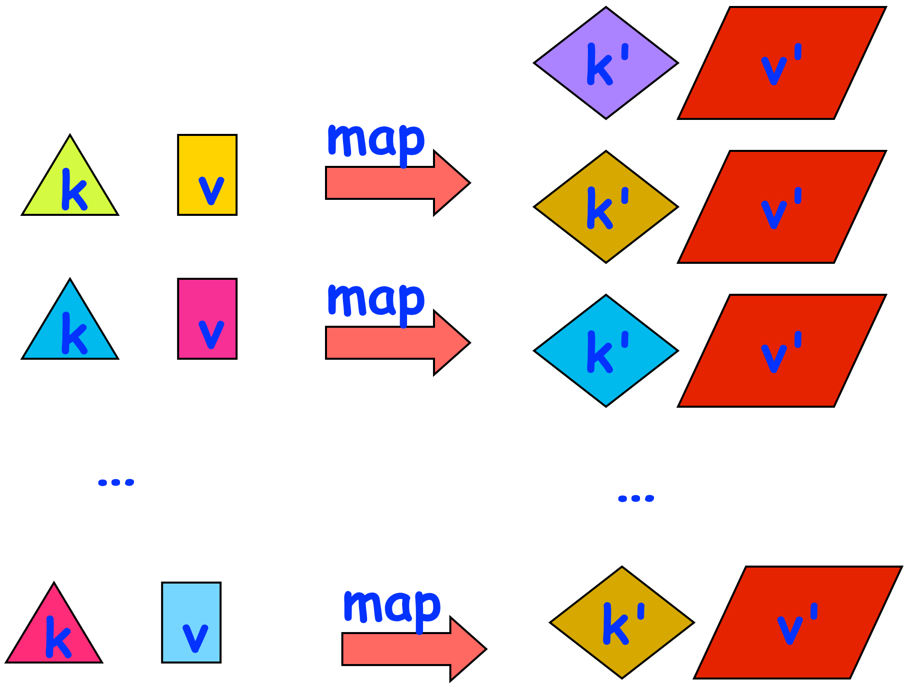
MapReduce Pattern

- Apply Map function f to user supplied record of key-value pairs
- Compute set of intermediate key/value pairs
- Apply Reduce operation g to all values that share same key to combine derived data properly
  - Often produces smaller set of values
- User supplies Map and Reduce operations in functional model so that the system can parallelize them, and also re-execute them for fault tolerance

MapReduce: The Map Step

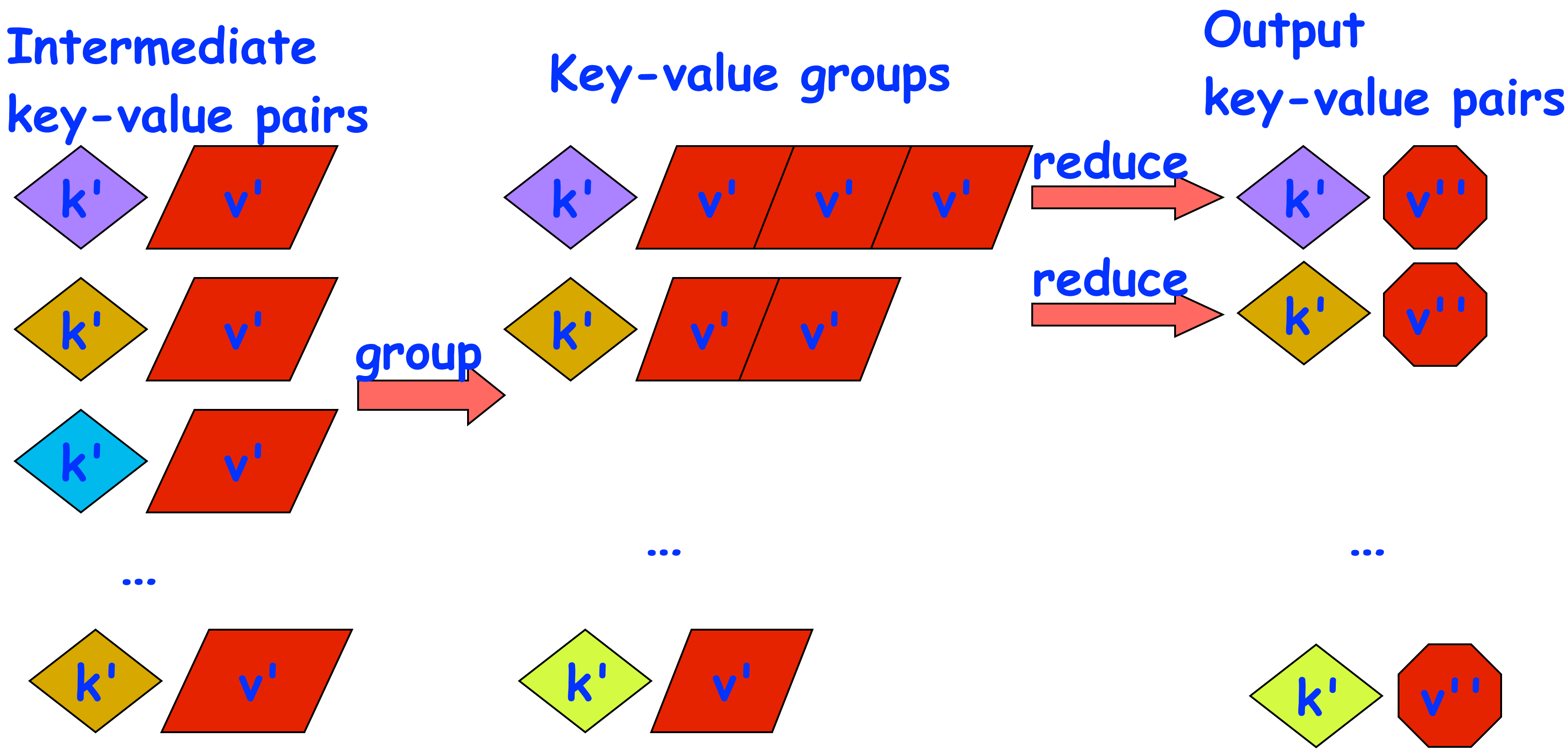
Input set of key-value pairs

Flattened intermediate set of key-value pairs



Source: http://infolab.stanford.edu/~ullman/mining/2009/mapreduce.ppt

MapReduce: The Reduce Step



Source: http://infolab.stanford.edu/~ullman/mining/2009/mapreduce.ppt

Map Reduce: Summary

- Input set is of the form {(k1, v1), . . . (kn, vn)}, where (ki, vi) consists of a key, ki, and a value, vi.
  - Assume that the key and value objects are immutable, and that equality comparison is well defined on all key objects.
- Map function f generates sets of intermediate key-value pairs, f(ki,vi) = {(k1' ,v1'),...(km',vm')}. The km' keys can be different from ki key in the map function.
  - Assume that a flatten operation is performed as a post-pass after the map operations, so as to avoid dealing with a set of sets.
- Reduce operation groups together intermediate key-value pairs, {(k', vj')} with the same k', and generates a reduced key-value pair, (k',v''), for each such k', using reduce function g

Google Uses MapReduce For …

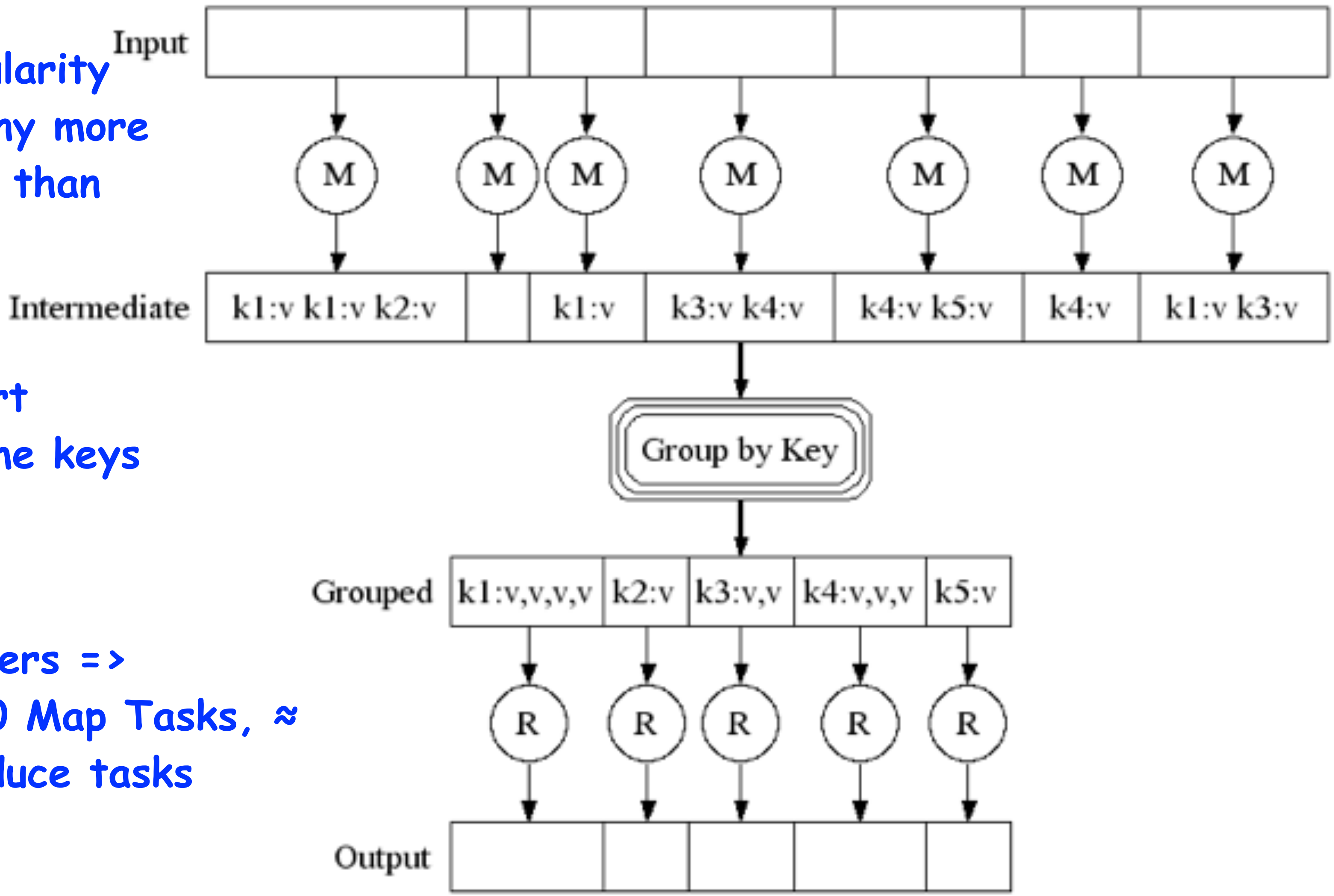
- Web crawl: Find outgoing links from HTML documents, aggregate by target document
- Google Earth: Stitching overlapping satellite images to remove seams and to select high-quality imagery
- Google Maps: Processing all road segments on Earth and render map tile images that display segments

MapReduce Execution

Fine granularity tasks: many more map tasks than machines

Bucket sort to get same keys together

2000 servers =>
≈ 200,000 Map Tasks, ≈ 5,000 Reduce tasks



WordCount example

In: set of words

Out: set of (word,count) pairs

Algorithm:

1. For each in word W, emit (W, 1) as a key-value pair (map step).
2. Group together all key-value pairs with the same key (reduce step).
3. Perform a sum reduction on all values with the same key(reduce step).

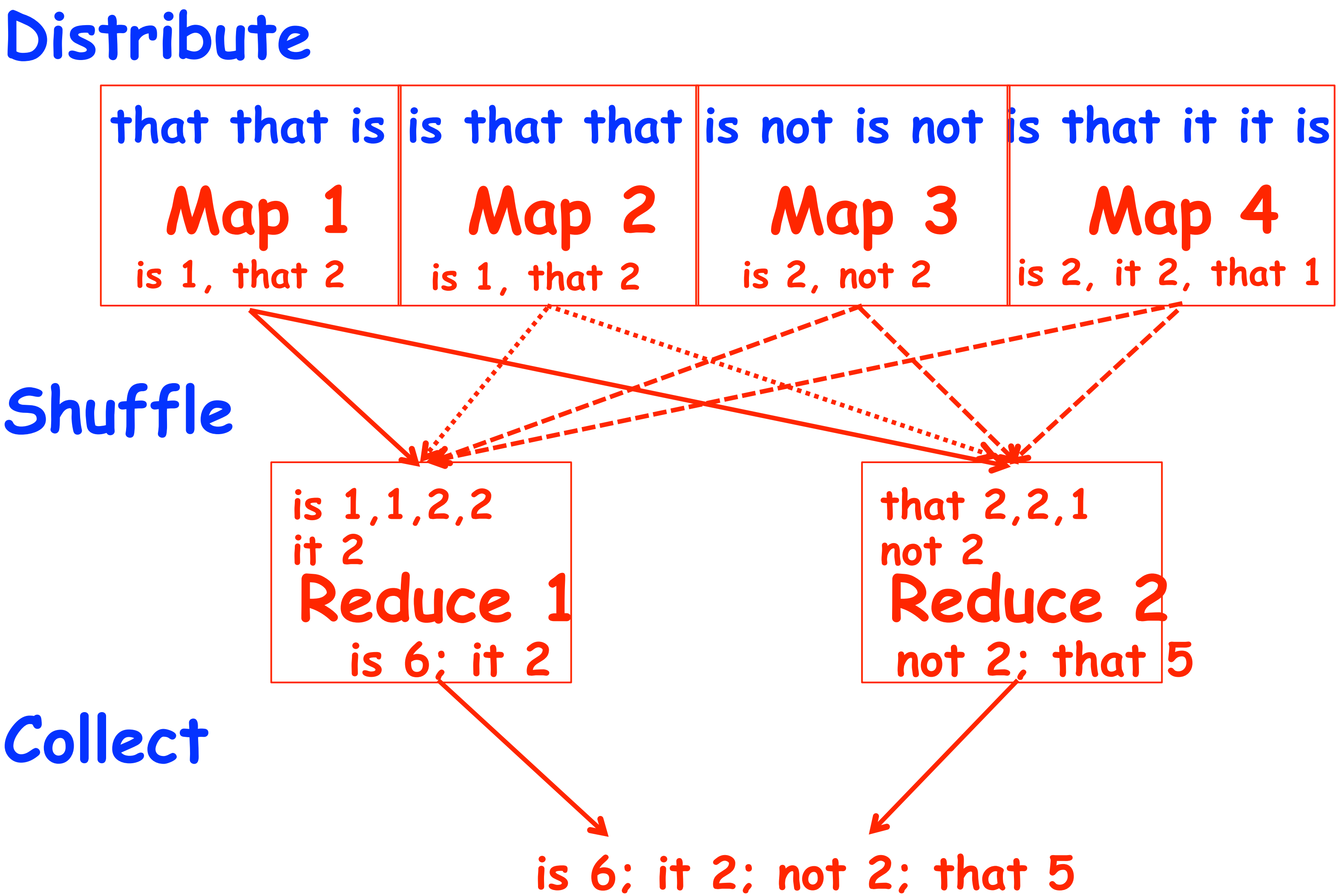
- All map operations in step 1 can execute in parallel with only local data accesses
- Step 2 may involve a major reshuffle of data as all key-value pairs with the same key are grouped together.
- Step 3 performs a standard reduction algorithm for all values with the same key, and in parallel for different keys.

PseudoCode for WordCount

```
<String, Integer> map(String inKey, String inValue):
  // inKey: document name
  // inValue: document contents
  for each word w in inValue:
    emitIntermediate(w, 1) // Produce count of words

<Integer> reduce(String outKey, Iterator<Integer> values):
  // outKey: a word
  // values: a list of counts
   Integer result = 0
   for each v in values:
     result += v // the value from map was an integer
   emit(result)
```

Example Execution of WordCount Program



Announcements & Reminders

- IMPORTANT:
  - Watch video & read handout for topic 2.5 and 2.6 for next lecture on Monday, Jan 29th
- HW2 is available and due by Wednesday, Feb 7th
- Quiz for Unit 1 (topics 1.1 - 1.5) is due by 11:59pm TODAY on Canvas
- See course web site for all work assignments and due dates
- Use Piazza (public or private posts, as appropriate) for all communications re. COMP 322
- See Office Hours link on course web site for latest office hours schedule.