Concurrency in Go

February 2025

Go Resources

https://tour.golang.org/list

https://play.golang.org

https://gobyexample.com

Today's Precept…

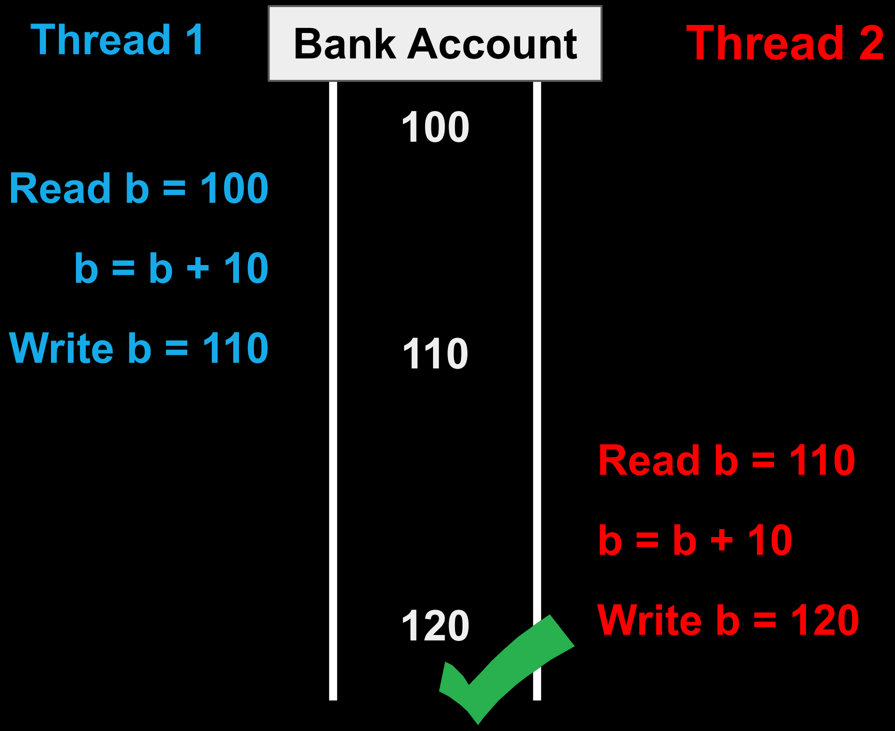
1. Two synchronization mechanisms
    a. Locks
    b. Channels
2. Mapreduce

Two synchronization mechanisms

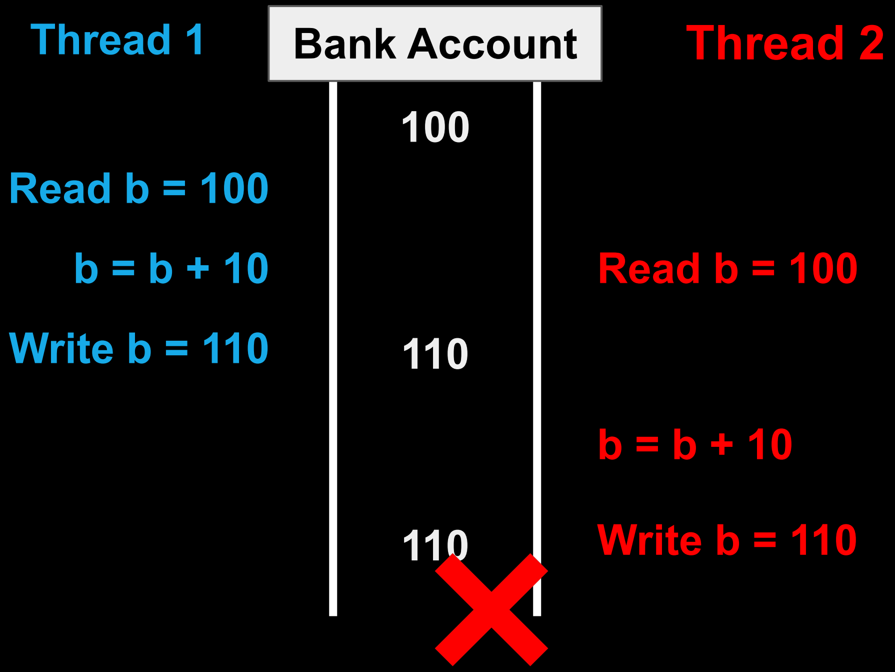
Locks - limit access to a critical section

Channels - pass information across processes using a queue

Example: Bank account



Example: Bank account



What went wrong?

Changes to balance are not ***atomic***

```
func Deposit(amount) {

    read balance
    balance = balance + amount
    write balance

}
```

What went wrong?

Suppose the function is called in two threads, with the Thread 1 chosen to run first.

Thread 1

```
func Deposit(amount) {

    read balance
    balance = balance + amount
    write balance

}
```

Thread 2

```
func Deposit(amount) {

    read balance
    balance = balance + amount
    write balance

}
```

What went wrong?

Suppose the function is called in two threads, with the Thread 1 chosen to run first.

Thread 1

```
func Deposit(amount) {

    read balance
    balance = balance + amount
    write balance

}
```

Thread 2

```
func Deposit(amount) {

    read balance
    balance = balance + amount
    write balance

}
```

What went wrong?

Then, an interrupt happens, and the OS scheduler selects Thread 2 to run.

Thread 1

```
func Deposit(amount) {

    read balance
    balance = balance + amount
    write balance

}
```

Thread 2

```
func Deposit(amount) {

    read balance
    balance = balance + amount
    write balance

}
```

What went wrong?

Thread 1 did not write new balance to shared storage, so Thread 2 reads the old value.

Thread 1

```
func Deposit(amount) {

    read balance
    balance = balance + amount
    write balance

}
```

Thread 2

```
func Deposit(amount) {

    read balance
    balance = balance + amount
    write balance

}
```

What went wrong?

This is called a **race condition**.

Thread 1

```
func Deposit(amount) {

    read balance
    balance = balance + amount
    write balance

}
```

Thread 2

```
func Deposit(amount) {

    read balance
    balance = balance + amount
    write balance

}
```

Solution - Locks

Changes to balance are now ***atomic.***

```
func Deposit(amount) {
    lock balanceLock
    read balance
    balance = balance + amount
    write balance
    unlock balanceLock
}
```

Critical section

Good Video Explanations

Race Conditions:
https://www.youtube.com/watch?v=FY9livorrJI

Deadlocks:
https://www.youtube.com/watch?v=LjWug2tvSBU

Locks in Go

```go
package account

import "sync"

type Account struct {
	balance int

}

func NewAccount(init int) Account {
	return Account{balance: init}
}
```

```go
func (a *Account) CheckBalance() int {

	return a.balance
}

func (a *Account) Withdraw(v int) {

	a.balance -= v
}

func (a *Account) Deposit(v int) {

	a.balance += v
}
```

Locks in Go

```go
package account

import "sync"

type Account struct {
	balance int
	mu sync.Mutex
}

func NewAccount(init int) Account {
	return Account{balance: init}
}
```

```go
func (a *Account) CheckBalance() int {
	a.mu.Lock()
	defer a.mu.Unlock()
	return a.balance
}

func (a *Account) Withdraw(v int) {
	a.mu.Lock()
	defer a.mu.Unlock()
	a.balance -= v
}

func (a *Account) Deposit(v int) {
	a.mu.Lock()
	defer a.mu.Unlock()
	a.balance += v
}
```

Read Write Locks in Go

```go
package account

import "sync"

type Account struct {
	balance int

}

func NewAccount(init int) Account {
	return Account{balance: init}
}
```

```go
func (a *Account) CheckBalance() int {
	a.rwLock.RLock()


}

func (a *Account) Withdraw(v int) {


	a.balance -= v
}

func (a *Account) Deposit(v int) {


	a.balance += v
}
```

Read Write Locks in Go

```go
package account

import "sync"

type Account struct {
	balance int
	rwLock sync.RWMutex
}

func NewAccount(init int) Account {
	return Account{balance: init}
}
```

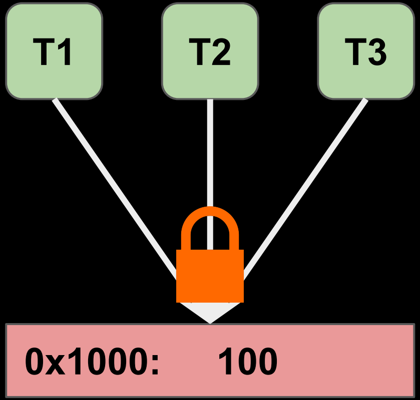
```go
func (a *Account) CheckBalance() int {
	a.rwLock.RLock()
	defer a.rwLock.RUnlock()
	return a.balance
}

func (a *Account) Withdraw(v int) {
	a.rwLock.Lock()
	defer a.rwLock.Unlock()
	a.balance -= v
}

func (a *Account) Deposit(v int) {
	a.rwLock.Lock()
	defer a.rwLock.Unlock()
	a.balance += v
}
```

Two Solutions to the Same Problem

Locks:

Multiple threads can reference same memory location

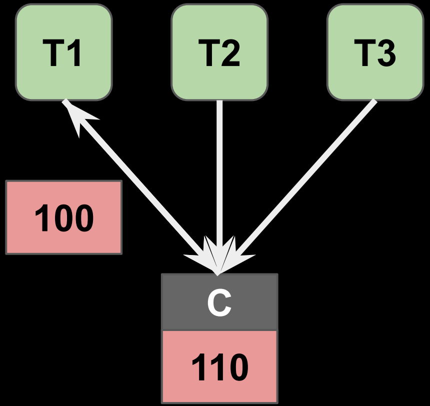
Use lock to ensure only one thread is updating it at any given time



Channels:

Data item initially stored in channel

Threads must request item from channel, make updates, and return item to channel



Bank Account Code (using channels)

```go
package account

type Account struct {
	// Fill in Here
}

func NewAccount(init int) Account {
	// Fill in Here
}
```

```go
func (a *Account) CheckBalance() int {
	// What goes Here?
}

func (a *Account) Withdraw(v int) {
	// ???
}

func (a *Account) Deposit(v int) {
	// ???
}
```

Bank Account Code (using channels)

```go
package account

type Account struct {
	balance chan int
}

func NewAccount(init int) Account {
	a := Account{
		balance: make(chan int, 1)
	}
	a.balance <- init
	return a
}
```

```go
func (a *Account) CheckBalance() int {
	// What goes Here?
}

func (a *Account) Withdraw(v int) {
	// ???
}

func (a *Account) Deposit(v int) {
	// ???
}
```

Bank Account Code (using channels)

```go
package account

type Account struct {
	balance chan int
}

func NewAccount(init int) Account {
	a := Account{
		balance: make(chan int, 1)
	}
	a.balance <- init
	return a
}
```

```go
func (a *Account) CheckBalance() int {
	bal := <-a.balance
	a.balance <- bal
	return bal
}

func (a *Account) Withdraw(v int) {
	// ???
}

func (a *Account) Deposit(v int) {
	//???
}
```

Bank Account Code (using channels)

```
package account

type Account struct {
	balance chan int
}

func NewAccount(init int) Account {
	a := Account{
		balance: make(chan int, 1)
	}
	a.balance <- init
	return a
}
```

```
func (a *Account) CheckBalance() int {
	bal := <-a.balance
	a.balance <- bal
	return bal
}

func (a *Account) Withdraw(v int) {
	bal := <-a.balance
	a.balance <- (bal - v)
}

func (a *Account) Deposit(v int) {
	//???
}
```

Bank Account Code (using channels)

```
package account

type Account struct {
	balance chan int
}

func NewAccount(init int) Account {
	a := Account{
		balance: make(chan int, 1)
	}
	a.balance <- init
	return a
}
```

```
func (a *Account) CheckBalance() int {
	bal := <-a.balance
	a.balance <- bal
	return bal
}

func (a *Account) Withdraw(v int) {
	bal := <-a.balance
	a.balance <- (bal - v)
}

func (a *Account) Deposit(v int) {
	bal := <-a.balance
	a.balance <- (bal + v)
}
```

Go channels

Channels also allow us to safely communicate between ***goroutines***

```go
result := make(chan int, numWorkers)

// Launch workers
for i := 0; i < numWorkers; i++ {
    go func() {
        doWork()
        result <- i
    }()
}

// Wait until all worker threads have finished
for i := 0; i < numWorkers; i++ {
    handleResult(<-result)
}
fmt.Println("Done!")
```

Go channels

Easy to express asynchronous RPC

Awkward to express this using locks

```go
result := make(chan int, numServers)

// Send query to all servers
for i := 0; i < numServers; i++ {
    go func() {
        resp := // ... send RPC to server
        result <- resp
    }()
}

// Return as soon as the first server responds
handleResponse(<-result)
```

Select statement

`select` allows a goroutine to wait on multiple channels at once

```
for {
    select {
        case money := <-dad:
            buySnacks(money)
        case money := <-mom:
            buySnacks(money)
    }
}
```

Select statement

`select` allows a goroutine to wait on multiple channels at once

```
for {
    select {
        case money := <-dad:
            buySnacks(money)
        case money := <-mom:
            buySnacks(money)
        case default:
            starve()
            time.Sleep(5 * time.Second)
    }
}
```

Handle timeouts using `select`

```go
// Asynchronously request an answer
// from server, timing out after X
// seconds
result := make(chan int)
timeout := make(chan bool)

// Ask server
go func() {
    response := // ... send RPC
    result <- response
}()

// Start timer
go func() {
    time.Sleep(5 * time.Second)
    timeout <- true
}()
```

```go
// Wait on both channels
select {
    case res := <-result:
        handleResult(res)
    case <-timeout:
        fmt.Println("Timeout!")
}
```

Exercise: Implementing a mutex using channels

```
type Lock struct {
	// ???
}

func NewLock() Lock {
	// ???
}

func (l *Lock) Lock() {
	// ???
}

func (l *Lock) Unlock() {
	// ???
}
```

Exercise: Implementing a mutex using channels

```go
type Lock struct {
	ch chan bool
}

func NewLock() Lock {
	// ???
}

func (l *Lock) Lock() {
	// ???
}

func (l *Lock) Unlock() {
	// ???
}
```

Exercise: Implementing a mutex using channels

```go
type Lock struct {
	ch chan bool
}

func NewLock() Lock {
	lock := Lock{make(chan bool, 1)}
	lock.ch <- true
	return lock
}

func (l *Lock) Lock() {
	// ???
}

func (l *Lock) Unlock() {
	// ???
}
```

Exercise: Implementing a mutex using channels

```
type Lock struct {
	ch chan bool
}

func NewLock() Lock {
	lock := Lock{make(chan bool, 1)}
	lock.ch <- true
	return lock
}

func (l *Lock) Lock() {
	<-lock.ch
}

func (l *Lock) Unlock() {
	// ???
}
```

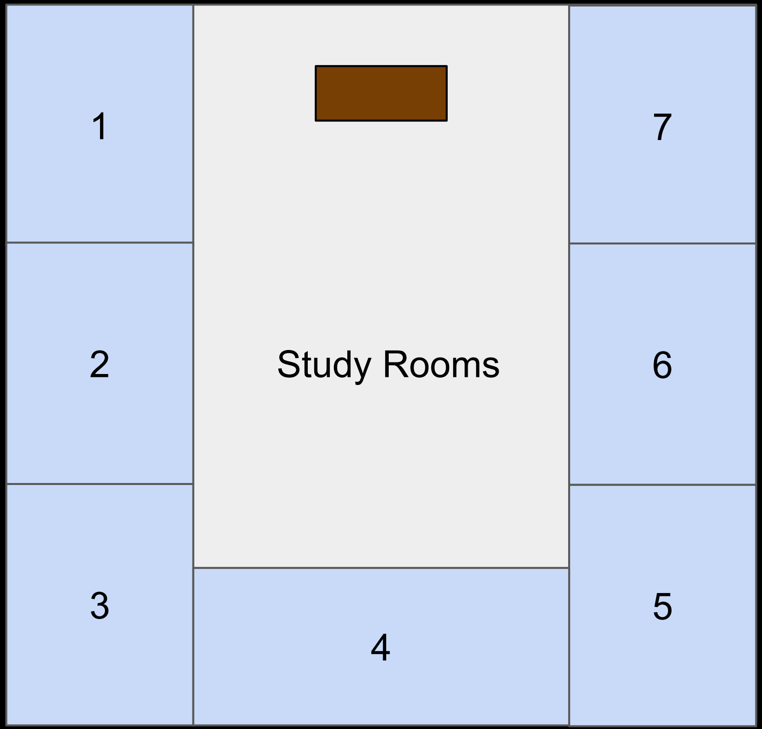
Exercise: Implementing a mutex using channels

```
type Lock struct {
    ch chan bool
}

func NewLock() Lock {
    lock := Lock{make(chan bool, 1)}
    lock.ch <- true
    return lock
}

func (l *Lock) Lock() {
    <-lock.ch
}

func (l *Lock) Unlock() {
    lock.ch <- true
}
```

Mutexes vs. Semaphores

Mutexes allow 1 process to enter critical section at a time. Allows at most *n* concurrent accesses

Semaphores allow up to **N** processes to enter critical section simultaneously



Outline

Two synchronization mechanisms

- Locks
- Channels

Mapreduce

Application: Word count

How much wood would a woodchuck chuck
if a woodchuck could chuck wood?

↓

`how: 1, much: 1, wood: 2, would: 1, a: 2, woodchuck: 2,`
`chuck: 2, if: 1, could: 1`

Application: Word count

Locally: tokenize and put words in a hash map

How do you parallelize this?

Partition the document into *n* partitions.

Build *n* hash maps, one for each partition

Merge the *n* hash maps (by key)

How do you do this in a distributed environment?

When in the Course of human events, it becomes necessary for one people to dissolve the political bands which have connected them with another, and to assume, among the Powers of the earth, the separate and equal station to which the Laws of Nature and of Nature's God entitle them, a decent respect to the opinions of mankind requires that they should declare the causes which impel them to the separation.

Input document

When in the Course of human events, it becomes necessary for one people to

---

dissolve the political bands which have connected them with another, and to assume,

---

among the Powers of the earth, the separate and equal station to which the Laws of

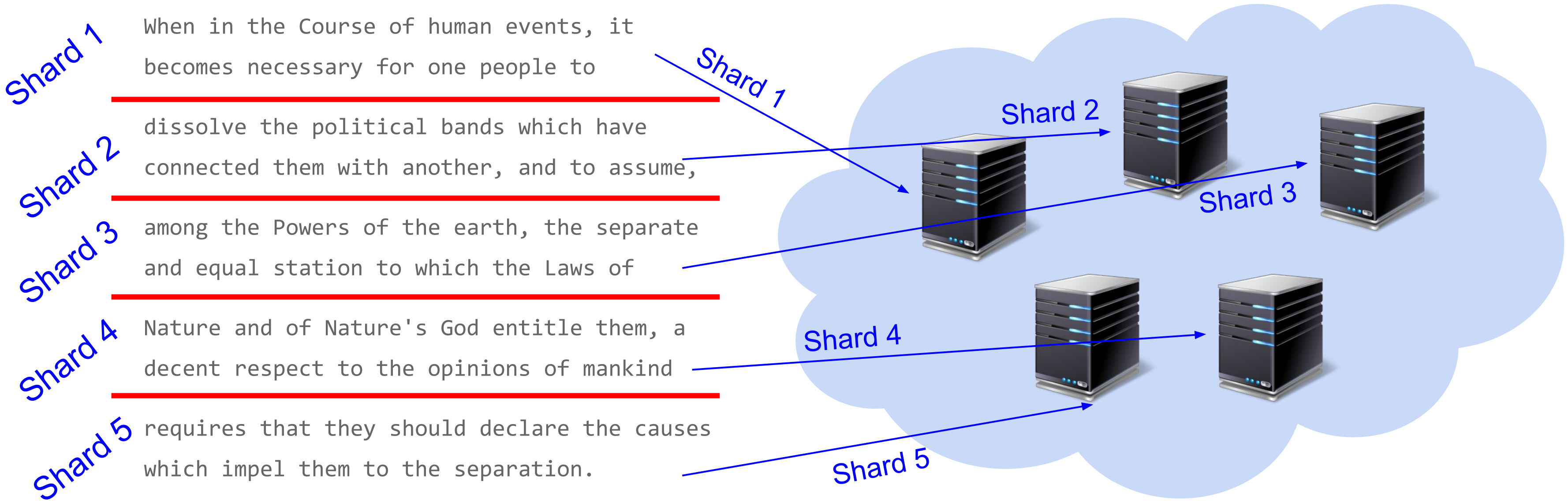
---

Nature and of Nature's God entitle them, a decent respect to the opinions of mankind

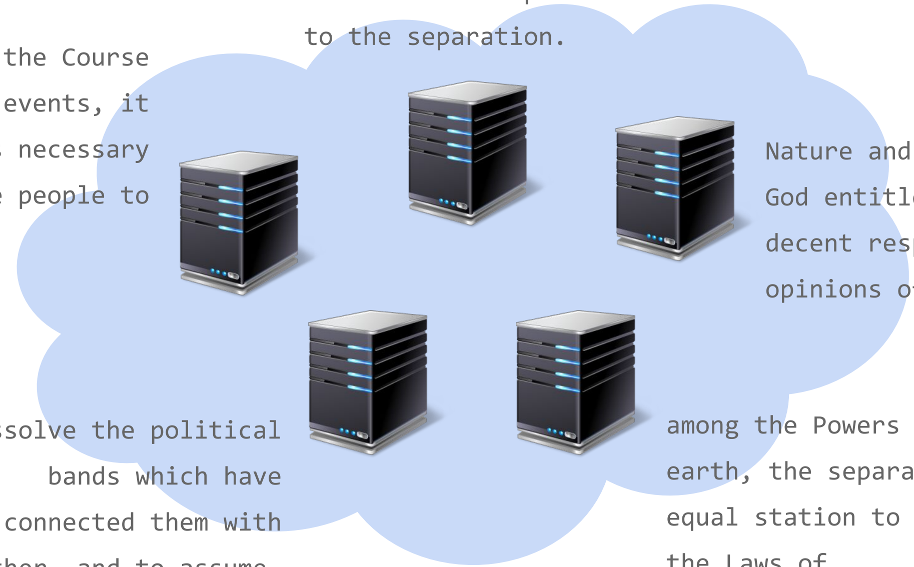
---

requires that they should declare the causes which impel them to the separation.

Partition


Shard 1
When in the Course of human events, it
becomes necessary for one people to
Shard 2
dissolve the political bands which have
connected them with another, and to assume,
Shard 3
among the Powers of the earth, the separate
and equal station to which the Laws of
Shard 4
Nature and of Nature's God entitle them, a
decent respect to the opinions of mankind
Shard 5
requires that they should declare the causes
which impel them to the separation.
Shard 1
Shard 2
Shard 3
Shard 4
Shard 5

Partition



When in the Course
of human events, it
becomes necessary
for one people to

dissolve the political
bands which have
connected them with
another, and to assume,

among the Powers of the
earth, the separate and
equal station to which
the Laws of

Nature and of Nature's
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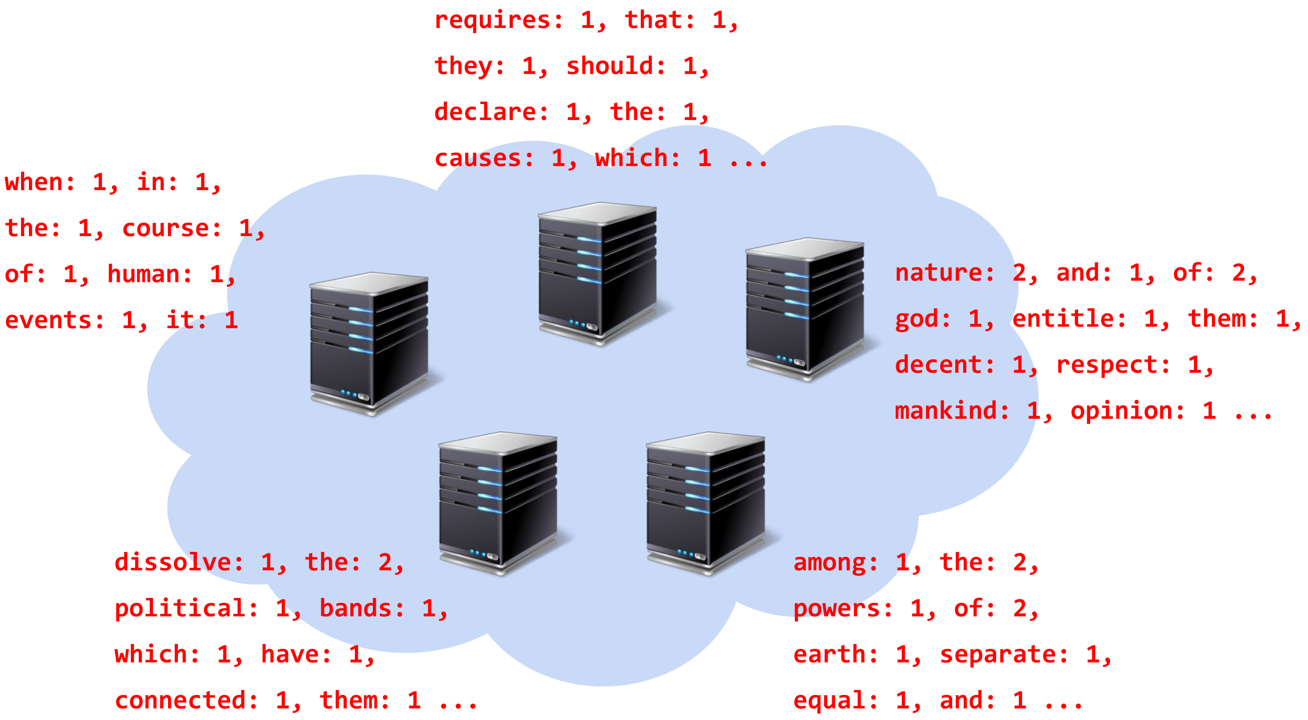
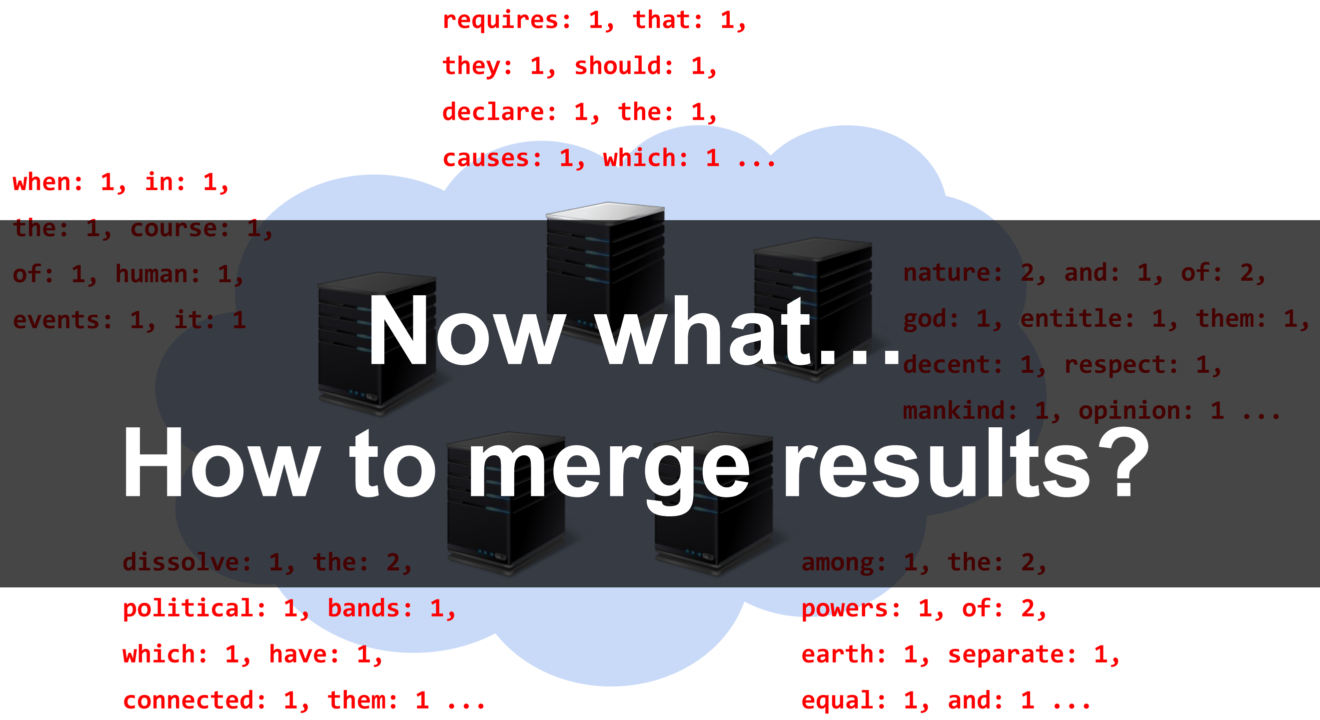
requires that they
should declare the
causes which impel them
to the separation.



Compute word counts locally

Now what...

How to merge results?



Compute word counts locally

Merging results computed locally

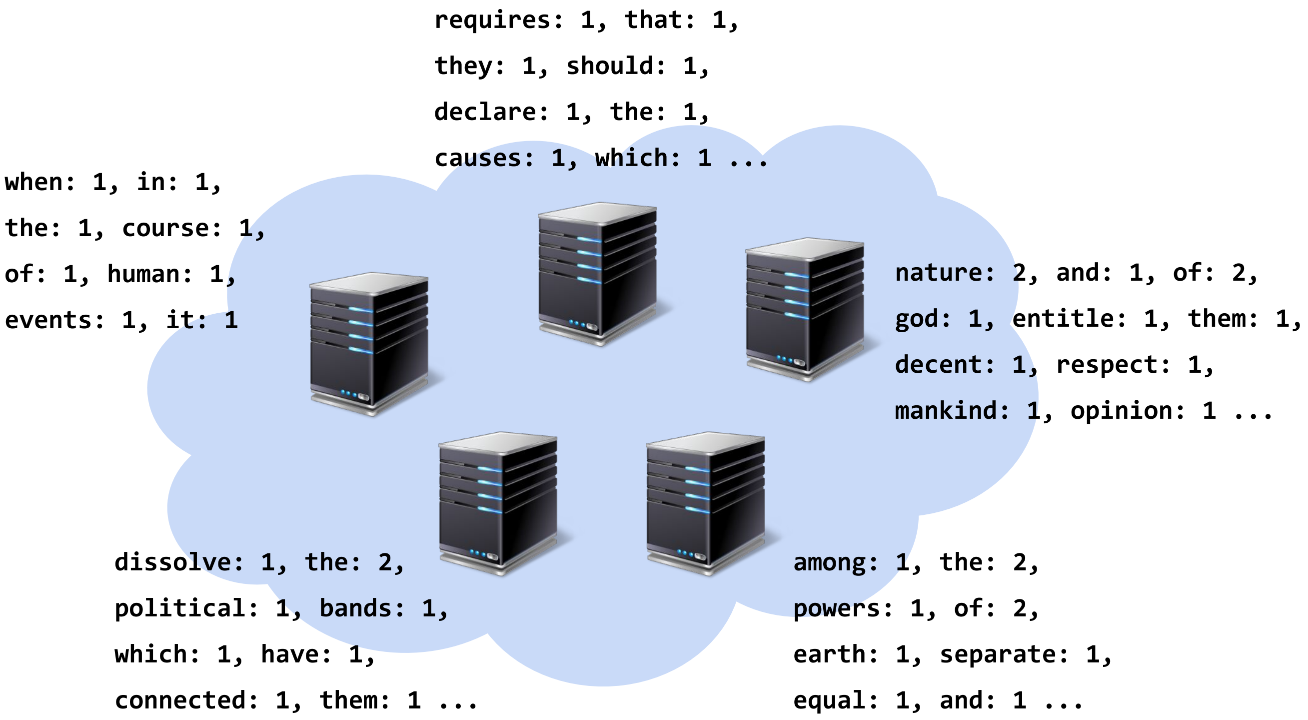
Several options

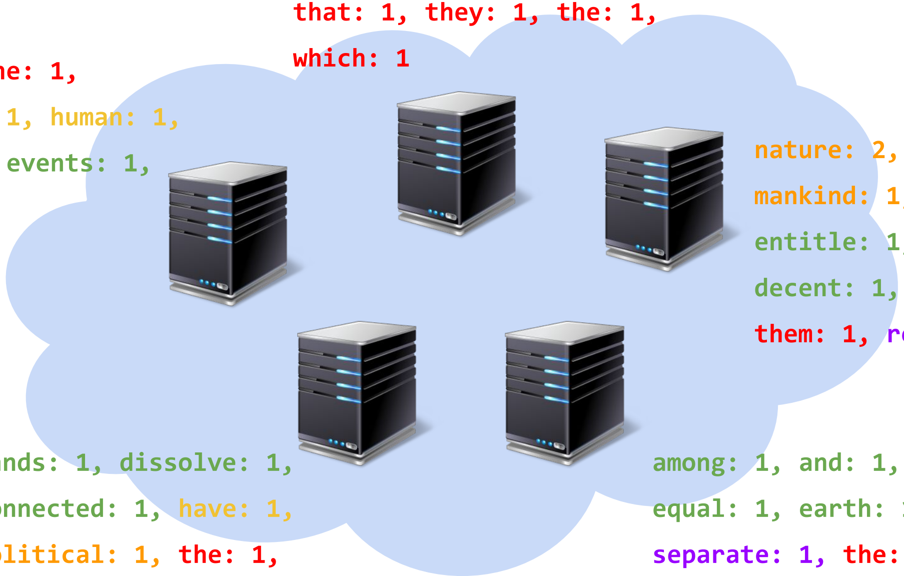
Don’t merge — requires additional computation for correct results

Send everything to one node — what if data is too big? Too slow…

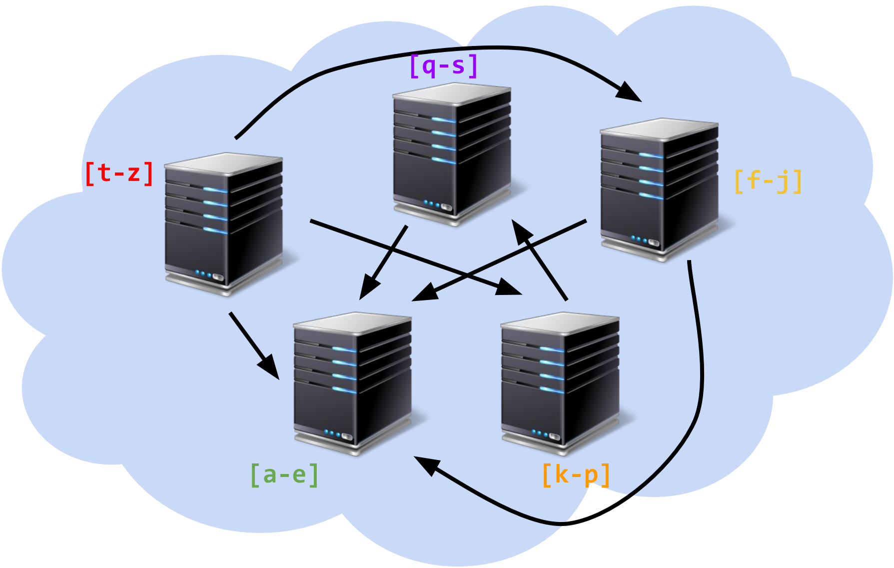
Partition key space among nodes in cluster (e.g. `[a-e]`, `[f-j]`, `[k-p]` ...)

1. Assign a key space to each node
2. Split local results by the key spaces
3. Fetch and merge results that correspond to the node’s key space


requires: 1, that: 1,
they: 1, should: 1,
declare: 1, the: 1,
causes: 1, which: 1 ...
when: 1, in: 1,
the: 1, course: 1,
of: 1, human: 1,
events: 1, it: 1
nature: 2, and: 1, of: 2,
god: 1, entitle: 1, them: 1,
decent: 1, respect: 1,
mankind: 1, opinion: 1 ...
dissolve: 1, the: 2,
political: 1, bands: 1,
which: 1, have: 1,
connected: 1, them: 1 ...
among: 1, the: 2,
powers: 1, of: 2,
earth: 1, separate: 1,
equal: 1, and: 1 ...

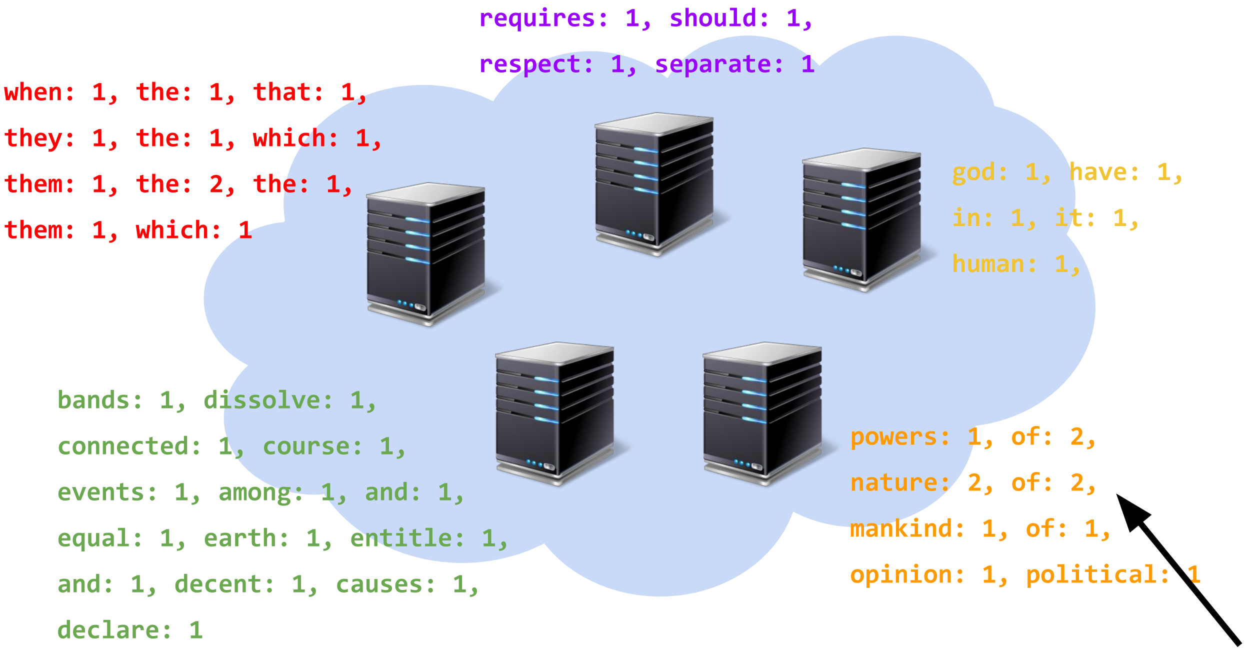


Split local results by key space

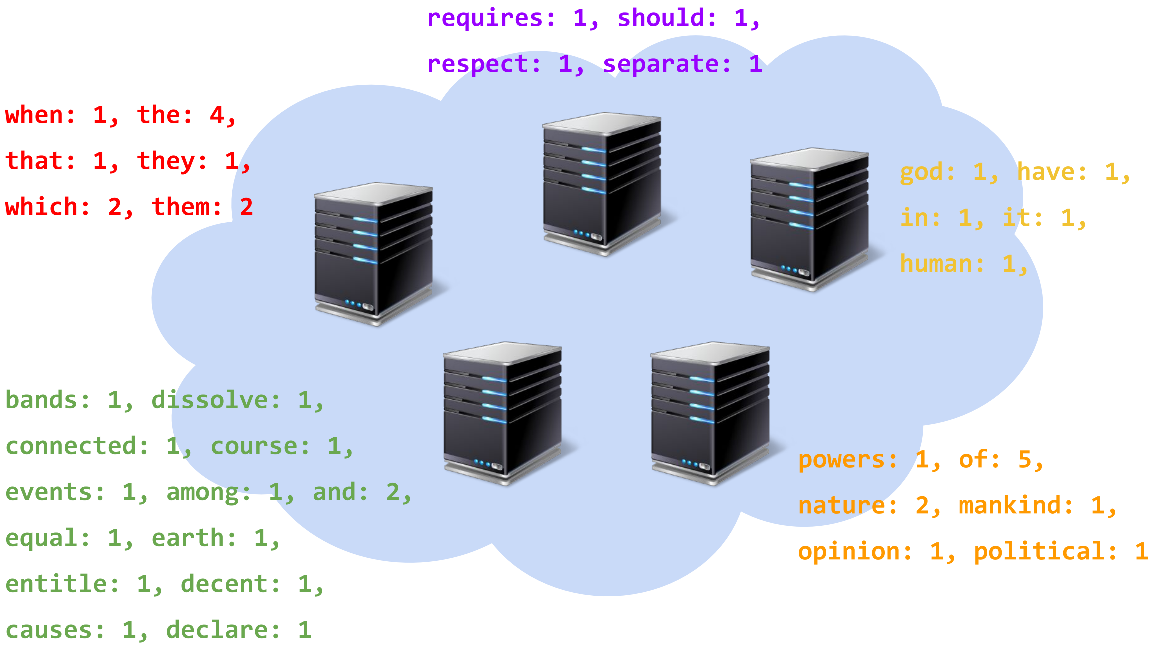


All-to-all shuffle

[a-e]
[f-j]
[k-p]
[q-s]
[t-z]



Note the duplicates...



Merge results received from other nodes

Mapreduce

Partition dataset into many chunks

Map stage: Each node processes one or more chunks locally

Reduce stage: Each node fetches and merges partial results from all other nodes

Mapreduce Interface

```
map(key, value) -> list(<k’, v’>)
```

Apply function to (key, value) pair

Outputs list of intermediate pairs

Mapreduce: Word count

```
map(key, value):
    // key = document name
    // value = document contents
    for each word w in value:
        emit (w, 1)
```

Mapreduce Interface

`map(key, value) -> list(<k’, v’>)`

Apply function to (key, value) pair

Outputs list of intermediate pairs

`reduce(key, list<value>) -> <k’, v’>`

Applies aggregation function to values

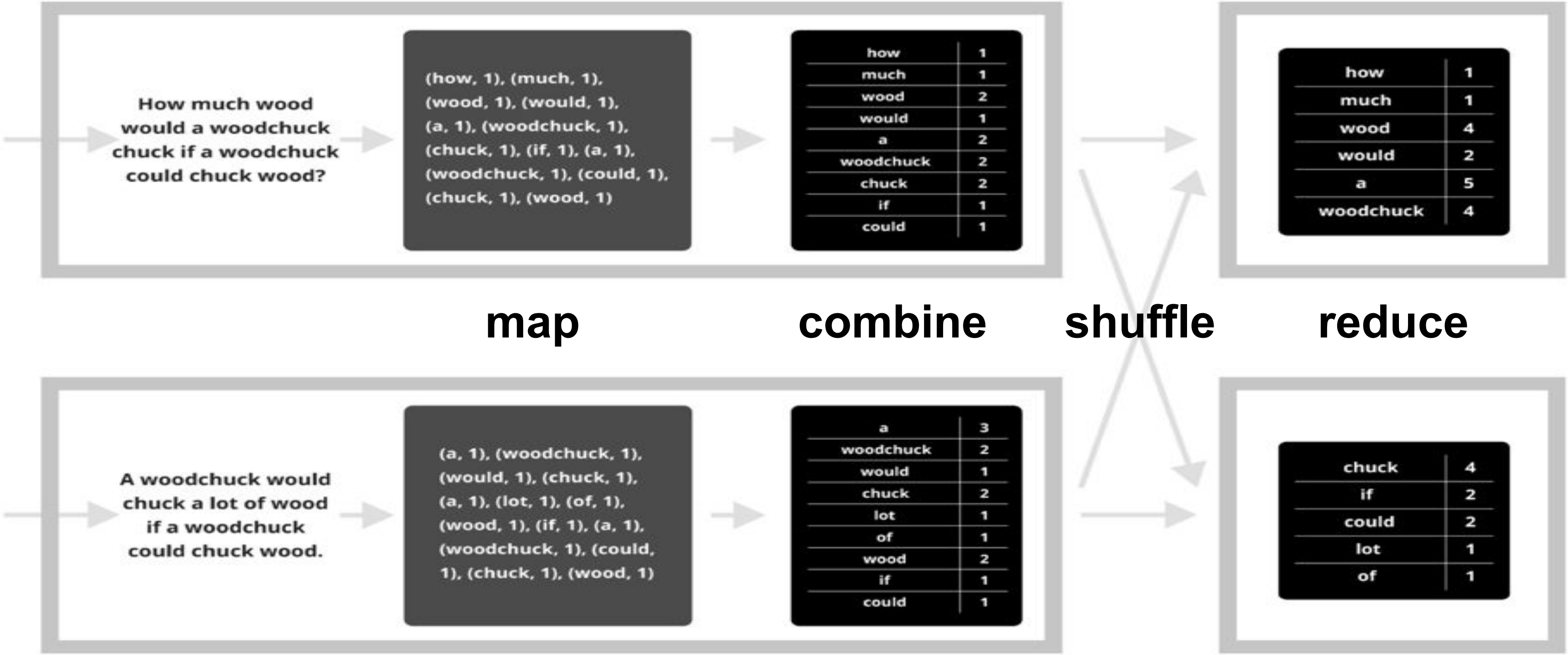
Outputs result

Mapreduce: Word count

```
map(key, value):
    // key = document name
    // value = document contents
    for each word w in value:
        emit (w, 1)

reduce(key, values):
    // key = the word
    // values = number of occurrences of that word
    count = sum(values)
    emit (key, count)
```

Mapreduce: Word count

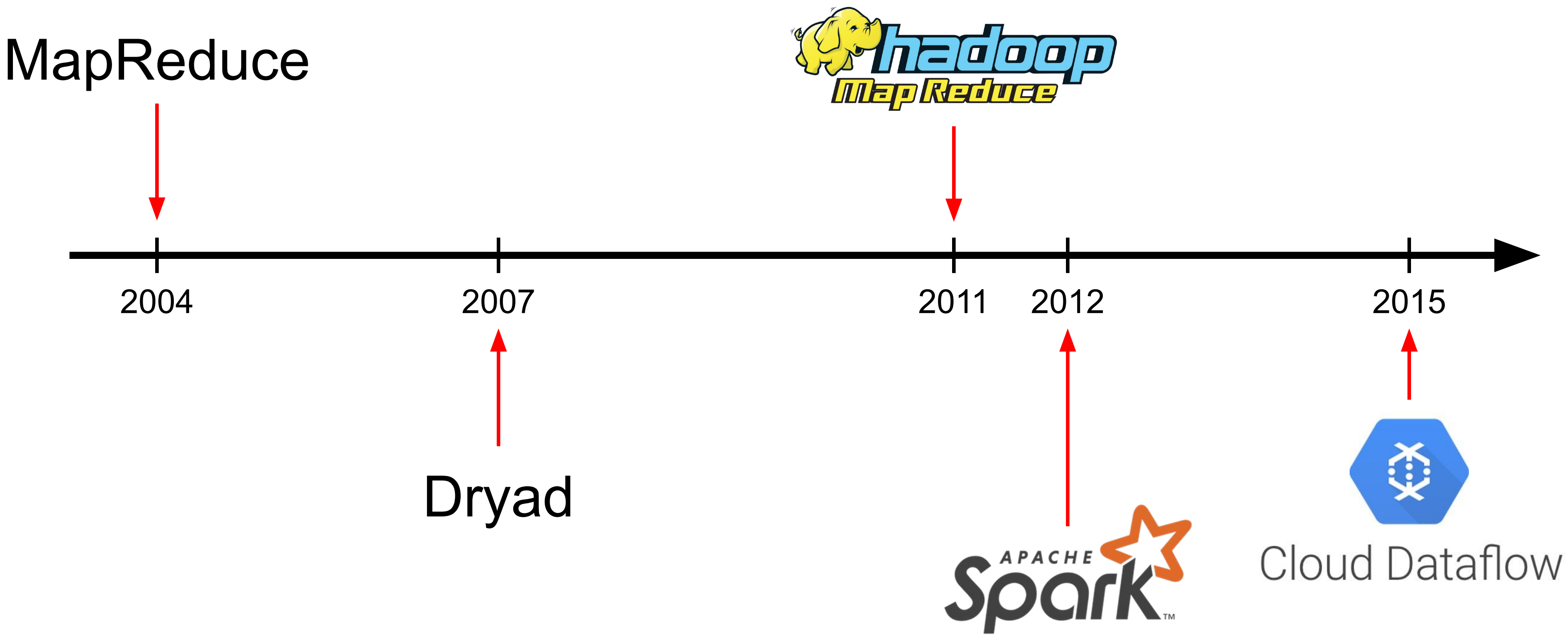


Why is implementing MapReduce hard?

- Failure is common
  - Even if each machine is available p = 99.999% of the time, a datacenter with n = 100,000 machines still encounters failures $(1-p^n) = 63\%$ of the time
- Data skew causes unbalanced performance across cluster

➔ Problems occur at scale.

➔ Hard to debug!


MapReduce
hadoop
Map Reduce
2004
2007
2011
2012
2015
Dryad
APACHE
Spark
Cloud Dataflow