

Parallel Programming

Learning Goals

- Recognize certain problems that arise while multiprocessing, such as difficulty of design and deadlock
- Create pipelines to increase the efficiency of repeated operations by executing sub-steps at the same time
- Use the MapReduce pattern to design parallelized algorithms for distributed computing

Designing Concurrent Algorithms

Last time, we discussed the four levels of concurrency used by computers: circuit-level concurrency, multitasking, multiprocessing, and distributed computing.

Today, we'll discuss how design algorithms so that they can run concurrently. This is often referred to as parallel programming.

We won't actually write parallelized code in this class (apart from a bit of MapReduce code where the parallelization is provided for us), but we will discuss common problems and algorithms in the field.

Difficulties in Parallelization

Difficulty of Design

Parallel programming is more difficult than regular programming because it forces us to think in new ways and adds new constraints to the problems we try to solve.

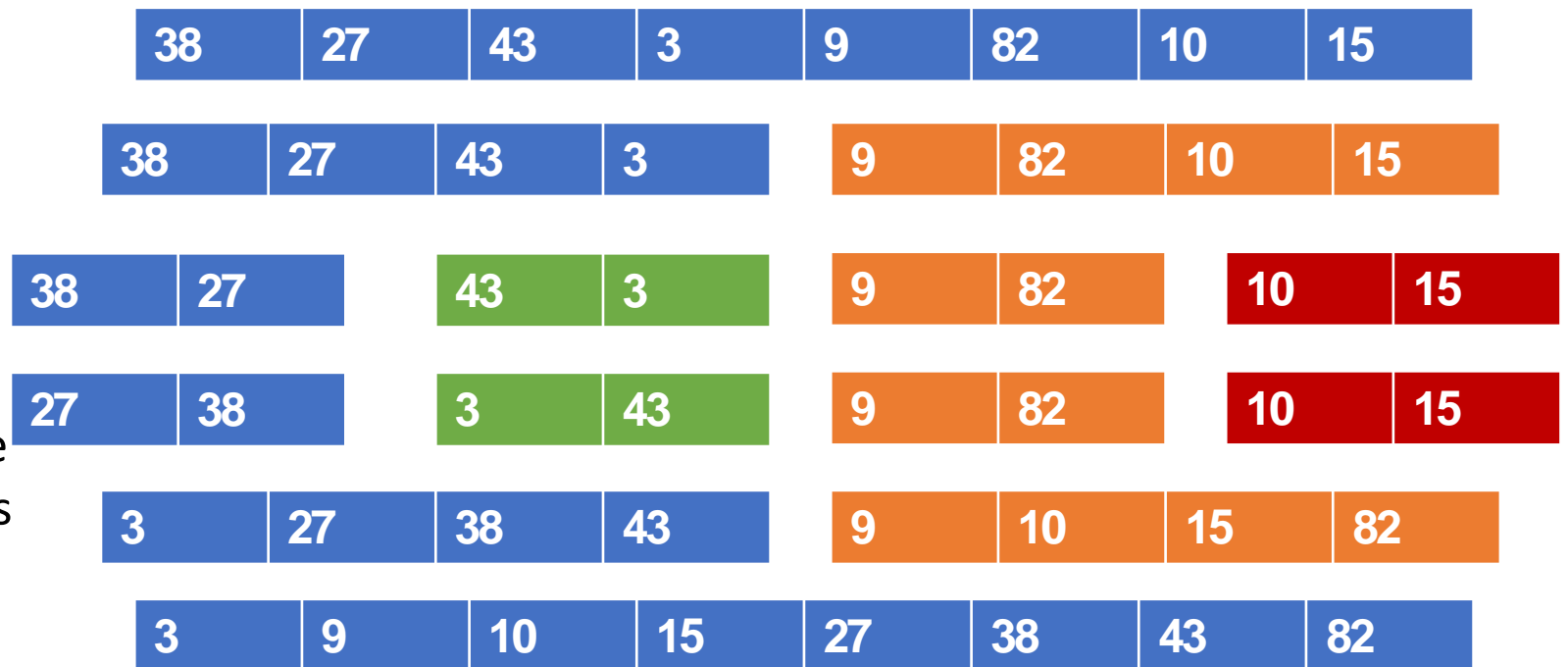
First, we must figure out how to design algorithms that can be split across multiple processes. This varies greatly in difficulty based on the problem we're solving!

Making Merge Sort Concurrent

Let's start with an easy example – Merge Sort. The algorithm for Merge Sort adapts nicely to concurrency; instead of running mergeSort on the two halves of the lists sequentially, run them concurrently. Then send the results back to a single core to be merged.

Assume each color is a different core. How many steps does a single core take in the worst case?

The blue core is the worst case. It does $n + n/2 + n/4 + \dots$ splits, then $\dots + n/4 + n/2 + n$ merges. The series $n + n/2 + n/4 + \dots$ approaches $2n$, so it does about $4n$ actions, or $O(n)$ work.



Making Loops Concurrent

It's easy to make recursive problems like merge sort concurrent if they make multiple recursive calls. It's harder to think concurrently when writing programs that use loops.

We could plan to identify all the iterations of the loop and run each iteration on a separate core. But what if the results of all the iterations need to be combined? And what if each iteration depends on the result of the previous one? This gets even harder if we don't know how many iterations there will be overall, like when we use a while loop.

A bit later, we'll talk about how to use algorithmic plans to address these difficulties.

```
def search(lst, target):  
    for item in lst:  
        if item == target:  
            return True  
    return False
```

```
def getSum(lst):  
    sum = 0  
    for item in lst:  
        sum = sum + item  
    return sum
```

```
def powersOf2(n):  
    i = 2  
    while i < n:  
        print(i)  
        i = i * 2
```

Sharing Resources

The next difficulty of writing parallel programs comes from the fact that multiple cores need to share individual resources on a single machine.

For example, two different programs might want to access the same part of the computer's memory at the same time. They might both want to update the computer's screen or play audio over the computer's speaker.

Locking and Yielding Resources

We can't just let two programs update a resource simultaneously- this will result in garbled results that the user can't understand. For example, if one program wants to print "Hello World" to the console, and the other wants to print "Good Morning", the user might end up seeing "Hello Good World Morning".

To avoid this situation, programs put a lock on a shared resource when they access it. While a resource is locked, no other program can access it.

Then, when a program is done with a resource, it yields that resource back to the computer system, where it can be sent to the next program that wants it.

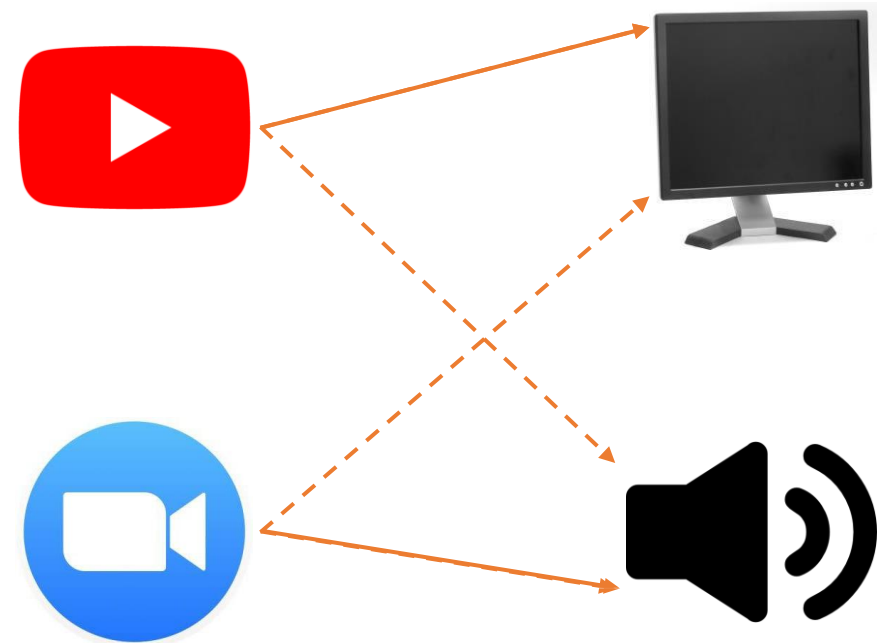
Note: if we want two programs to use a resource simultaneously, we usually use a third program to combine the actions together, and that third program is the one that accesses the resource. For example, if you listen to music while watching a lecture recording, your computer mixes the two audio tracks together and plays the combined result.

Deadlock Stalls the System

In general, this system of locking and yielding fixes most cases where programs might try to use a resource at the same time. But there are some situations where it can cause trouble.

Two programs, YouTube and Zoom, both want to access the screen and audio. They put their requests in at the same time, and the computer gives the screen to YouTube and the audio to Zoom.

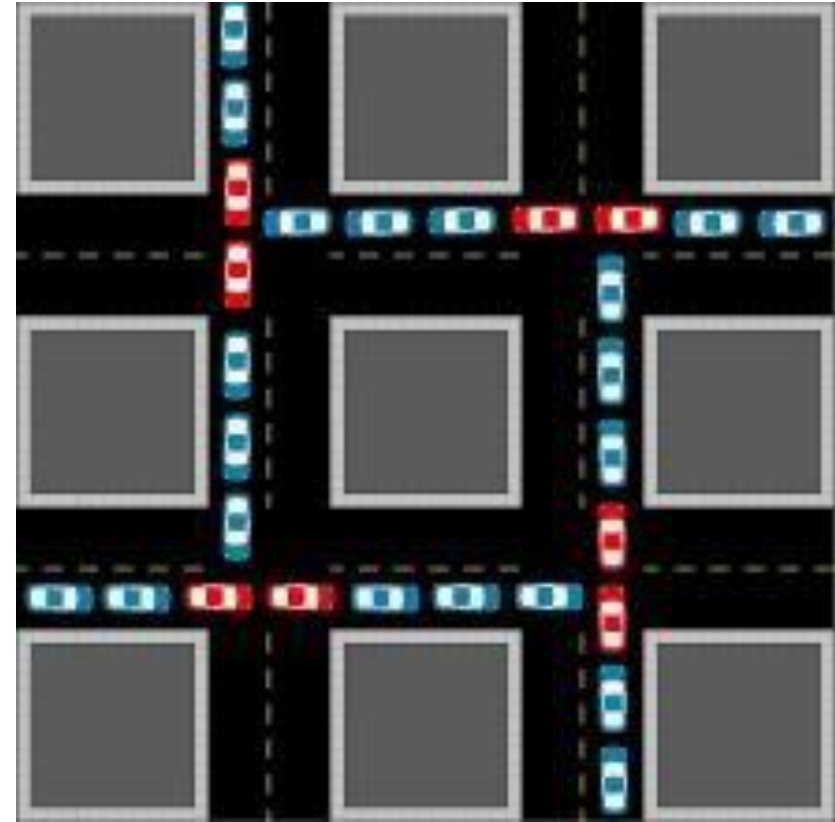
Both programs will lock the resource they have, then wait for the next resource to become available. Since they're waiting on each other, they'll wait forever! This is known as deadlock.



Deadlock Definition

In general, we say that deadlock occurs when two or more processes are all waiting for some resource that other processes in the group already hold. This will cause all processes to wait forever without proceeding.

Deadlock can happen in real life! For example, if enough cars edge into traffic at four-way intersections, the intersections can get locked such that no one can move forward.

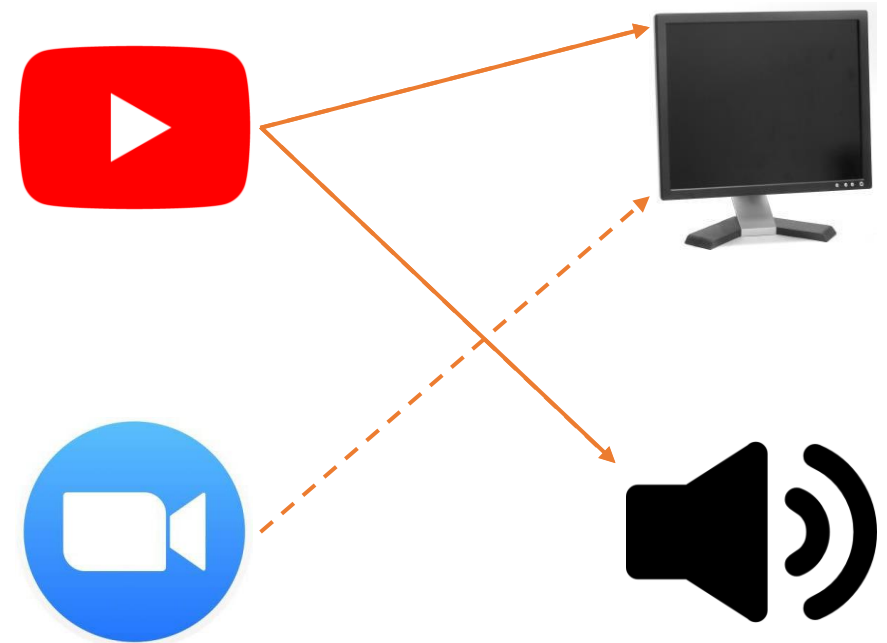


Fix Deadlock With Ordered Resources

In order to fix deadlock, impose an order that programs always follow when requesting resources.

For example, maybe YouTube and Zoom must receive the screen lock before they can request the audio. When YouTube gets the screen, it can make a request for the audio while Zoom waits for its turn.

When YouTube is done, it will yield its resources and Zoom will be able to access them.

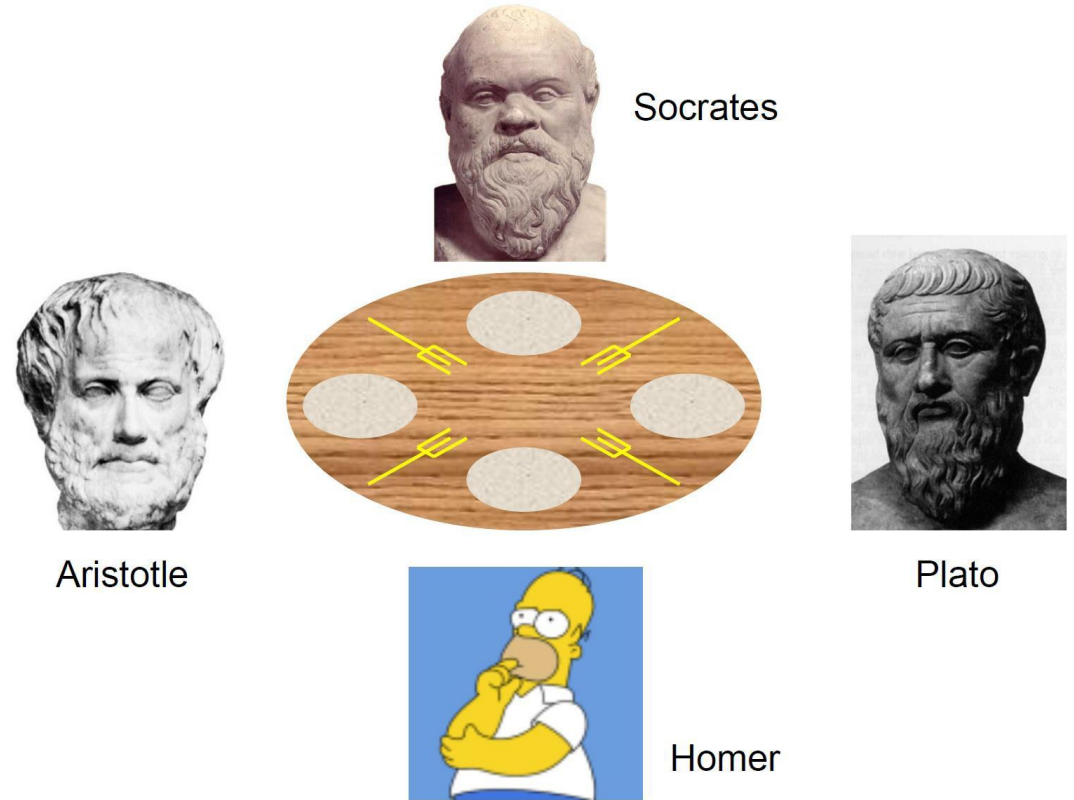


Activity: Dining Philosophers

Another example of deadlock occurs in the Dining Philosophers problem.

Several philosophers sit down at a circular table to eat. Each thinks for a while, then picks up their left fork, then picks up their right fork, then eats a bit. Then they put down the forks to think some more, then eat some more, etc.

You do: How can these philosophers get into deadlock? How can we solve that deadlock?



Some Processes Need to Communicate

We can't always guarantee that the processes running concurrently on a computer are independent. Sometimes a single program is split into multiple tasks that run concurrently instead.

These tasks might need to share partial results as they run. They'll need a way to communicate with each other.

Processes Pass Messages to Share Data

Data is shared between processes by passing messages. When one task has found a result, it may send it to the other process before continuing its own work.

If one process depends on the result of another, it may need to halt its work while it waits on the message to be delivered. This can slow down the concurrency, as it takes time for data to be sent between cores or computers.

Example: consider merge sort. Once a core has finished splitting it will need to wait for the result of the alternate core to merge the two halves of the list together.

Pipelining and MapReduce

Writing algorithms that can pass messages is tricky. We'll discuss two approaches that make it easier: pipelining and MapReduce.

The core idea behind pipelining is that you can parallelize an algorithm by splitting up the algorithm into a series of consecutive steps.

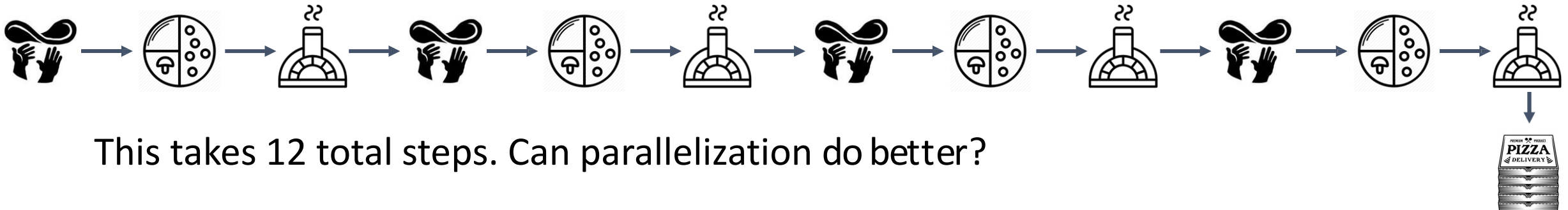
The core idea behind MapReduce is that you can parallelize an algorithm by splitting up the data into many many small parts.

Message Passing Example: Line Cooking

Let's introduce our two algorithms through the lens of line cooking. To make a pizza, we must:

1. Flatten the dough
2. Apply the toppings
3. Bake in the oven

If we need to make four pizzas without parallelization, it will look like this:



Pipelining

Pipelining Definition

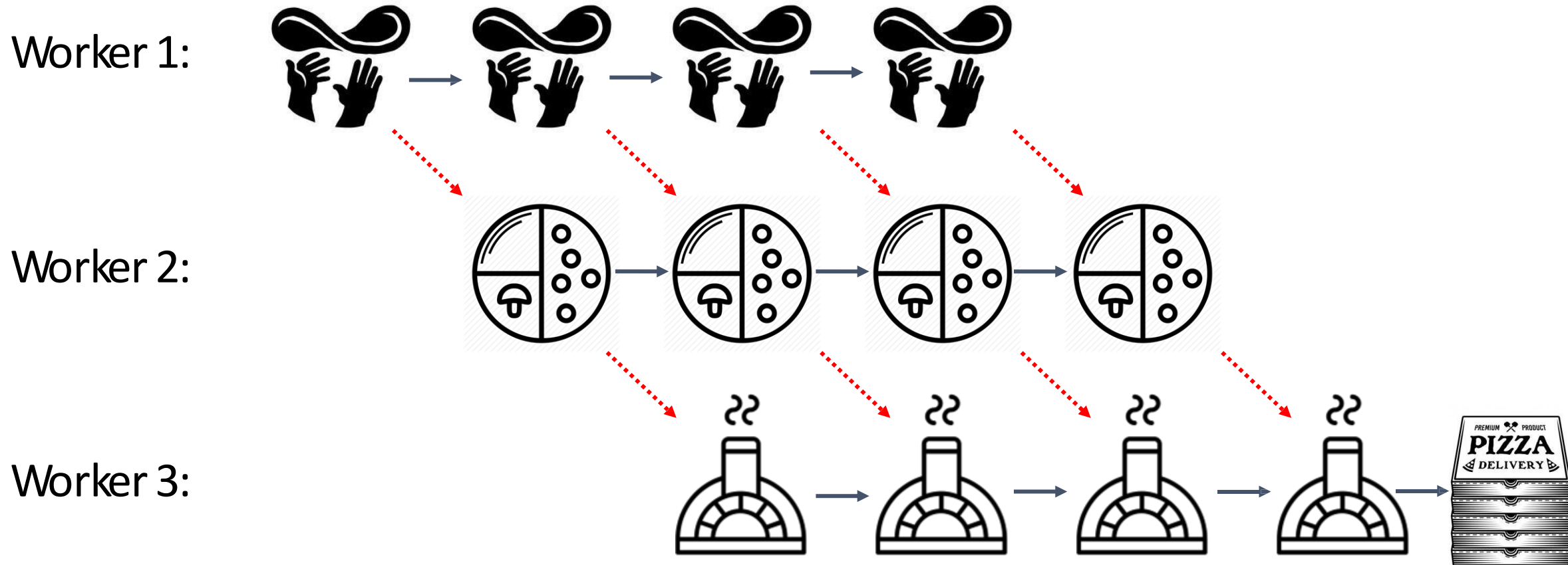
One algorithmic process that simplifies parallel algorithm design is pipelining. In this process, you start with a task that repeats the same procedure over many different pieces of data.

The steps of the procedure are split across different cores. Each core is like a single worker on an assembly line; when it is given a piece of data it executes the step, then passes the result to the next core.

Just like in an assembly line, the cores can run multiple pieces of data simultaneously by starting new computations while the others are still in progress.



Pizza Pipelining - 3 workers, 1 oven, 6 time-steps



Each worker has one task. #1 flattens dough, #2 arranges toppings, #3 bakes in the oven. There are still 12 total steps, but there are only 6 time-steps.

Rules for Pipelining

When designing a pipeline, it's important to remember that each step relies on the step that came before it. You cannot start applying toppings until the dough has been flattened.

Additionally, the length of time that the pipelining process takes depends on the longest step. If flattening dough and applying toppings are fast (maybe 5 minutes each) but cooking in the oven is slow (maybe 20 minutes), the whole process will have to wait on the slowest step to conclude.

Benefits of Pipelining

Pipelining is most useful when the number of shared resources is limited. For example, in pizza-making we may have only one oven; using pipelining ensures that we are constantly making use of the oven without wasting time.

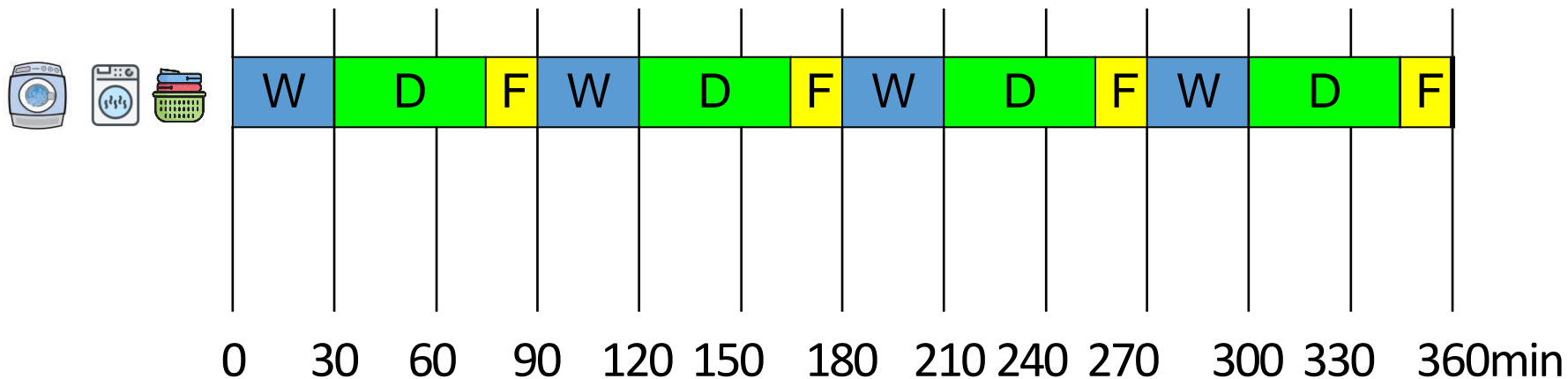
Pipelining is also useful for tasks that require setup time, but then can run many times without further setup - maybe for flattening, the cook only has to clean the counter and flour it once.

Another Example: Laundry Without Pipelining

You probably already use pipelining when you do laundry. Let's look at an example where we assume you need to wash, dry, and fold several loads of laundry.

Washing [W] takes 30 minutes; drying [D] takes 45; folding [F] takes 15.

If you don't use pipelining and wait until a load of laundry is folded before starting the next one, doing four loads of laundry takes six hours.

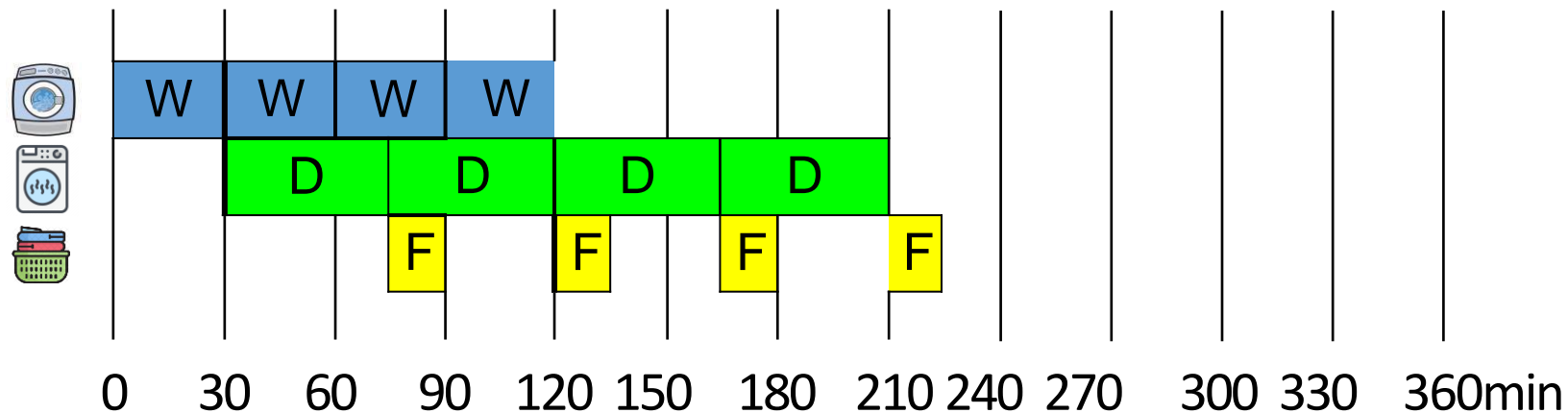


Example: Laundry With Pipelining

To use pipelining, split the three steps of the laundry process across three workers: the washer, dryer, and folder. Each worker has a lock on the shared resource.

With pipelining, four loads of laundry only takes 3 hours and 45 minutes. Much faster!

[In reality, you alternate between these tasks and the machines do the work; you just start the machines. So the machines are the workers in this scenario.]



Activity: Design a Pipeline

The process of writing a thank-you card has three sequential steps: Writing the note [10min], Adding the address to the envelope [6min], and Stuffing the envelope [6min]. Because you hate writing thank-you cards, you've decided to hire two helpers (your younger siblings) to help with the work.

You need to write all the notes yourself, to make sure they're personalized, but you can outsource the other tasks to the helpers once the card has been written

By yourself, you can write 2 full sets of thank-you cards in an hour (plus part of a third). If you use pipelining and the three workers (yourself + two helpers), how many completed thank-you cards can you make in an hour?

Hint: try drawing this out the way we drew out the washer/dryer/folder example, but with writer/adder/stuffer as the three roles.

Pipelining in Computer Science

Pipelining is used to increase the efficiency of certain operations in computer science, like matrix multiplication. It's also used in the Fetch-Execute cycle, which is how the CPU processes instructions.

Pipelining is often combined with multiprocessing to split the operations being performed across multiple cores. This helps ensure that no core goes unused.

MapReduce

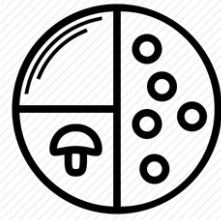
MapReduce Organizes Concurrency

Another popular algorithm for organizing parallelized programs is called MapReduce. Instead of breaking up a procedure's steps across different cores, this algorithm takes a large data set and breaks up the data itself across the cores.

This is a really effective approach if you have a lot of cores to work with (like in distributed computing). It's also a great approach for any problem over big data – that is, giant data sets that take far too long to process sequentially.

MapReduce - 4 workers, 4 Ovens, 3 time-steps

Worker 1:



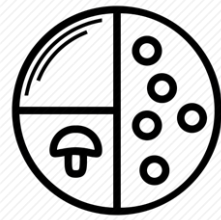
Worker 2:



Worker 3:



Worker 4:



Each worker makes one pizza instead of doing one task repeatedly.

If we have infinite ovens and infinite workers, we can make as many pizzas as we want in just 3 time-steps!

Making MapReduce Algorithms

The MapReduce approach is simple enough that we can discuss how to build algorithms that actually use it.

A MapReduce algorithm is composed of three parts.

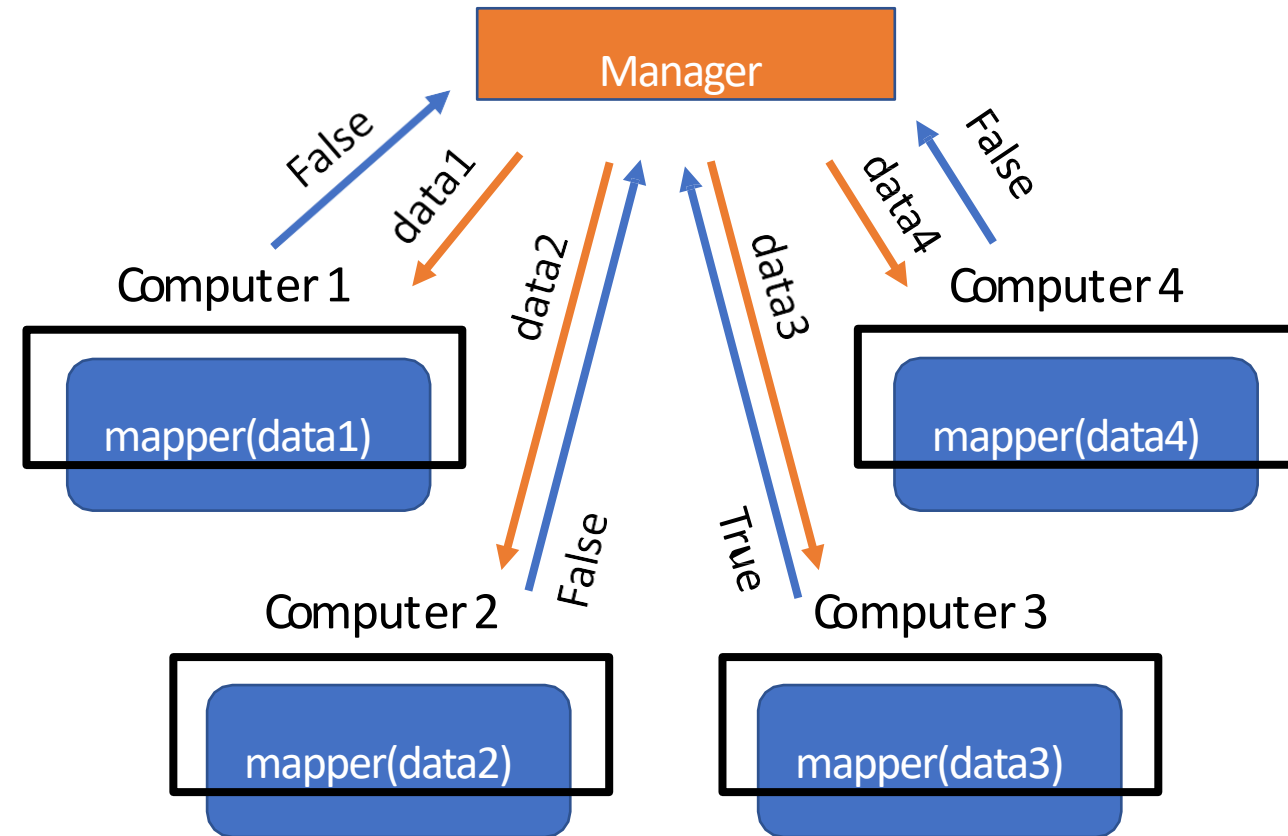
- The mapper takes a piece of data, processes it, and finds a partial result
- The reducer takes a set of results and combines them together
- The manager moves data through the process and outputs the final result
 - Splits up data, sends to mappers, get results back
 - Combines results together, sends to the reducer
 - Gets the final result, outputs it

MapReduce Example: Search – Mapper

Let's say we want to search a book for a specific word. How can we split up this task?

First, the manager divides the book into many small parts- maybe one page per part. It sends each page to a different computer.

Each computer runs its copy of the mapper on its page. It returns True if it finds the result, and False otherwise. These results are sent back to the manager.

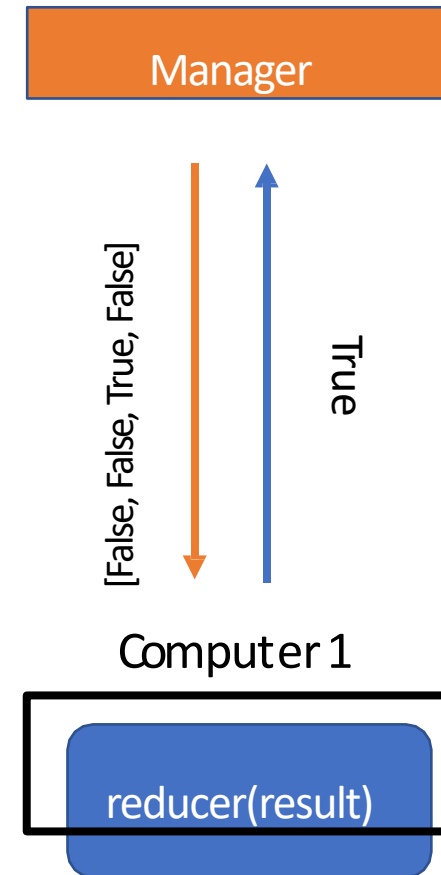


MapReduce Examples: Search – Reducer

Once all the mappers have returned their results the manager puts them all in a list and sends that list to the reducer(s). The reducer combines the results together in some way.

There can be more than one reducer if there are lots of results to combine or if we're checking multiple things (like searching for more than one word). For now, we'll just use one.

Our reducer will check all of the results and send **True** back to the manager if any of them are **True**.



Coding MapReduce

We provide a version of the MapReduce manager in the demo that uses multiprocessing to run the algorithm on several cores at the same time.

That makes implementing MapReduce easy- we just need to write code for the mapper and the reducer.

It's hard to tell that the system uses multiprocessing, but we can print out partial work to show what's happening. You need to end the process (by clicking the 'Terminate and restart the interpreter' button) to see what was printed in the individual calls.

```
# Assume the page is in a file
def mapper(filename, target):
    # don't worry about reading/cleaning files # yet – we'll get there soon!
    text = cleanFile(readFile(filename))
    words = text.split(" ")
    for i in range(len(words)):
        word = words[i]
        if word == target:
            print("file", f, "found on word #", i)
            return True
    print("file", f, "didn't find it")
    return False
```

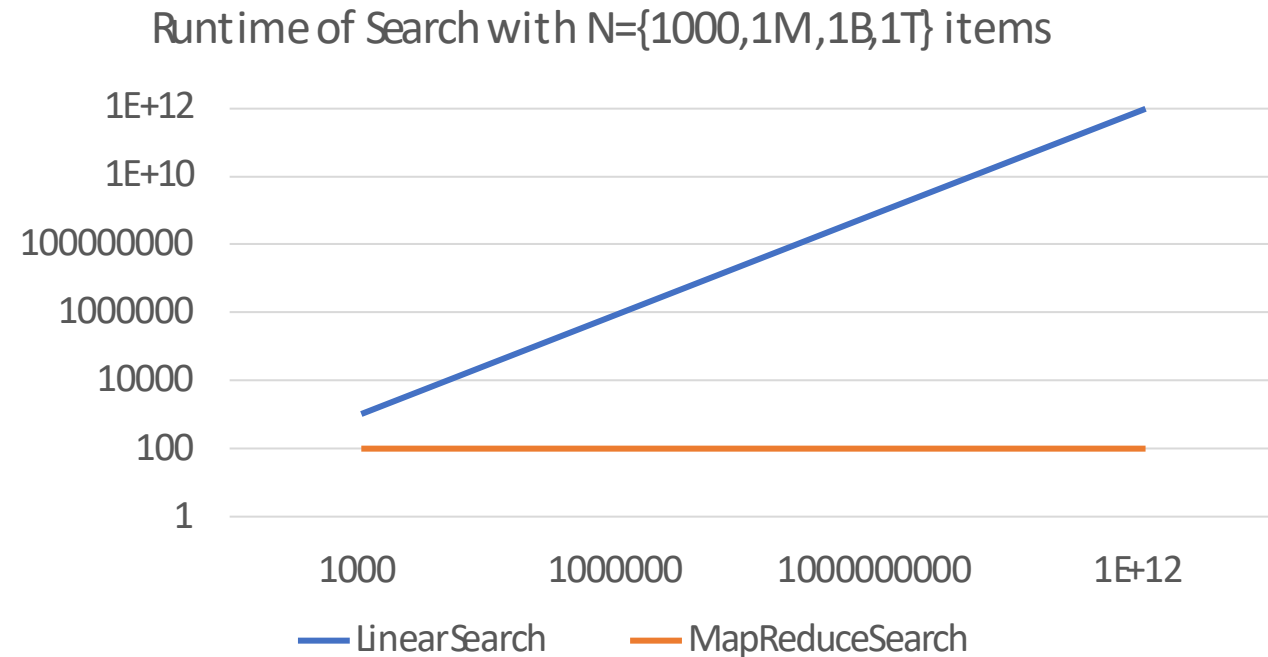
```
# If the word is on any page, return True
def reducer(lst):
    print("reducer is checking", lst)
    for pageResult in lst:
        if pageResult == True:
            return True
    return False
```

MapReduce Efficiency

MapReduce can process huge data sets and get results quickly because it takes a list of length N and breaks it up into constant-size parts.

The core assumption is that we have enough computers to make the data pieces really small. If we process 1 million data points with 100,000 computers, each computer only needs to handle 100 data points.

This is similar to the logic behind hashing!



Another Example: Counting

What if we instead wanted to count the number of words across all of Wikipedia?

First, the manager breaks up the data- maybe each Wikipedia entry goes to a computer.

The mapper can take a single page and count all the words on it.

The manager takes all those counts and puts them in a list.

The reducer takes the list of numbers and returns their sum.

Activity: MapReduce the Class (if time)

Let's use MapReduce to determine how many students in a class belong to each country.

We'll assign everyone to a breakout room with ~10 people in it. In the breakout room, designate one person as the notetaker (the mapper). That person must tally how many people in the room are in each of the different countries.

When we rejoin the main room, the notetaker will report their results to the chat. The instructor will then act as the reducer and combine the results.