PARALLEL PROCESSING

CS435 Distributed Systems

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TOPICS

- Parallel computing
- Parallel programming
- Java Threads Library
- Parallel program using Shared Memory

Most of the content in these set of slides is based on “A Sophomoric Introduction to Shared-Memory Parallelism and Concurrency”, Dan Grossman, online notes, version Feb 2012

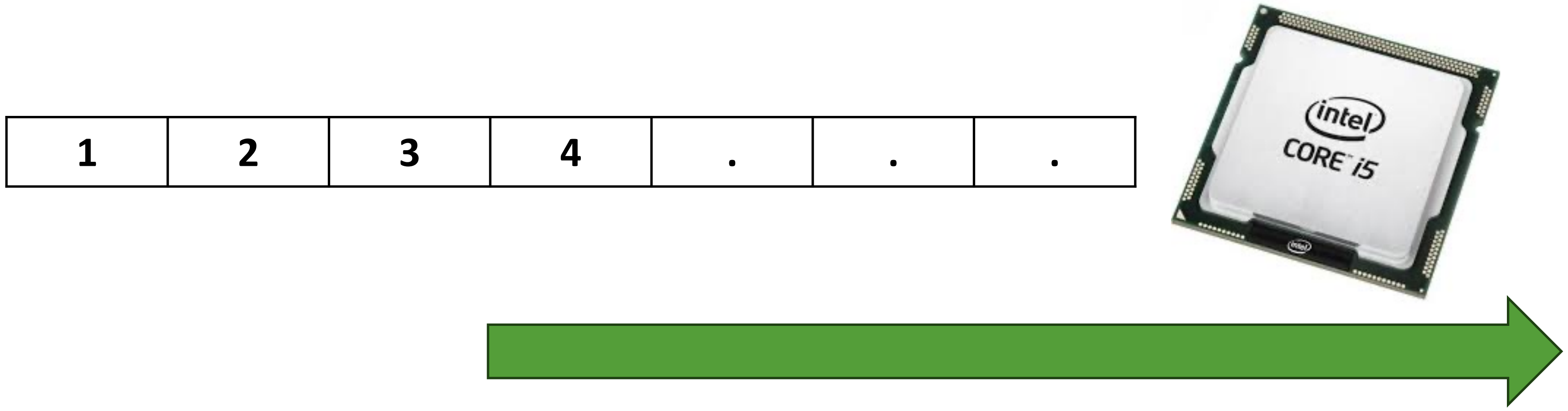
PARALLEL COMPUTING

PARALLEL COMPUTING

So far, most or all of your study of computer science has assumed that

one thing happens at a time

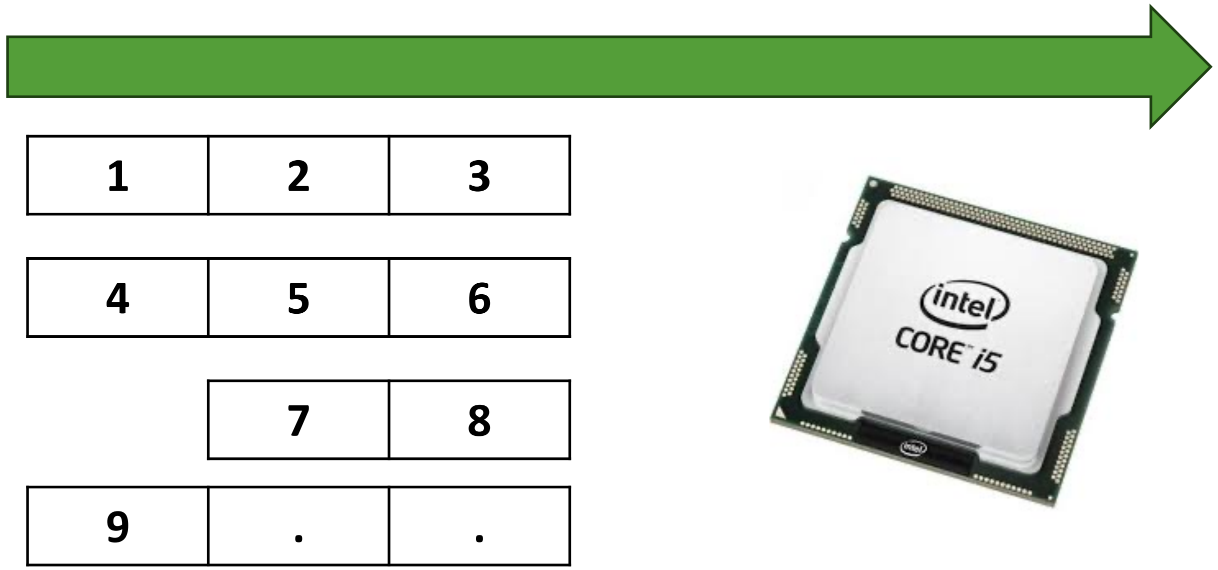
- This is sequential programming
- Everything is part of one sequence



PARALLEL COMPUTING

Parallelism: Divide and Conquer ??

- Opportunities
  - Divide work among threads of execution
  - Faster runtimes
  - Thread programming
  - More throughput = speedup
  - Concurrent access to resources
- Challenges
  - Harder to write parallel code
  - Performance issues
  - Concurrency issues



PARALLEL COMPUTING

Supercomputing

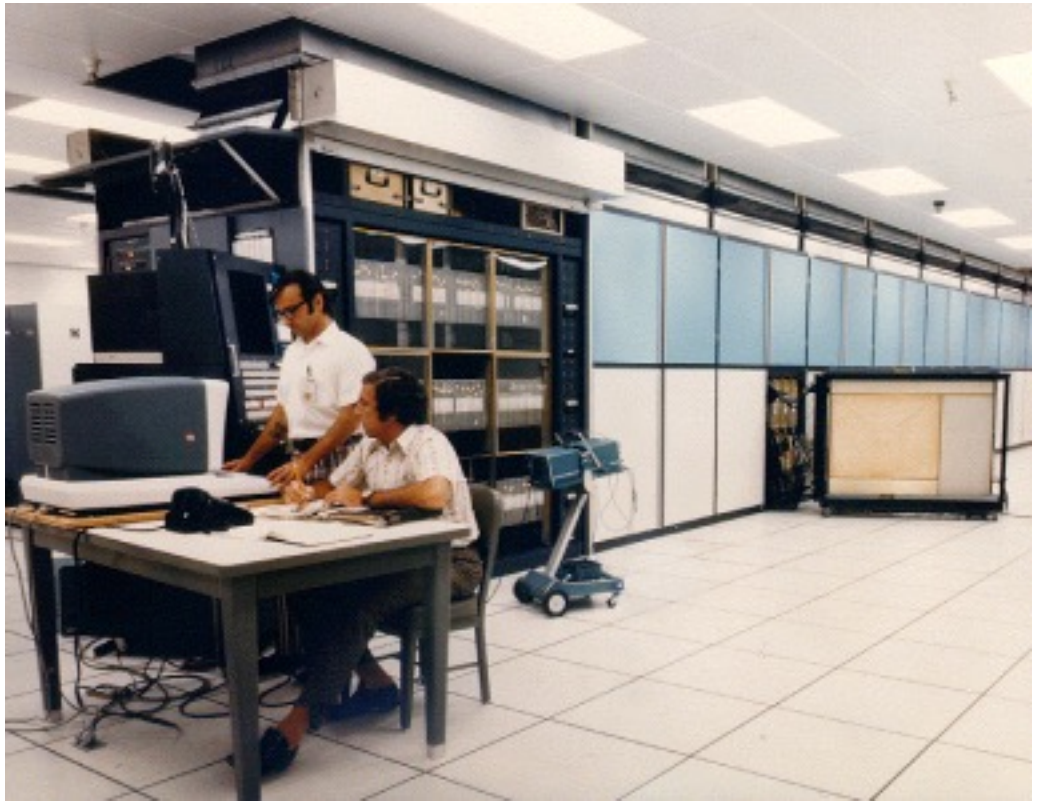
- Since 1960s
- First IBM UNIVAC_LARC in Lawrence Livermore National Laboratory
- LARC supported multiprocessing with two CPUs (called Computers) and an input/output (I/O) Processor (called the Processor).
- One addition operation tool about 4 microseconds

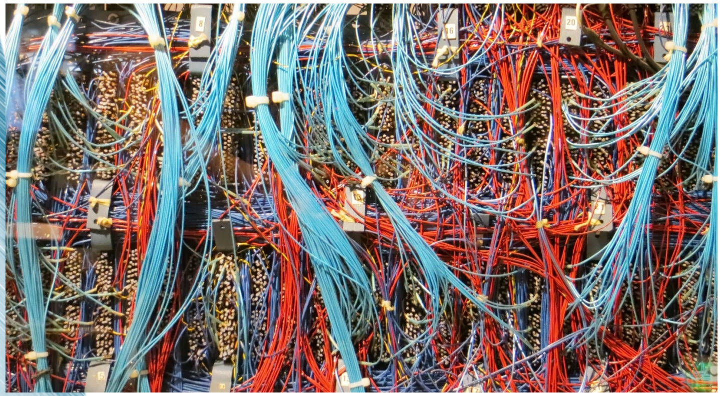
https://en.wikipedia.org/wiki/UNIVAC_LARC

PARALLEL COMPUTING

Supercomputing

- The ILLIAC IV was the first massively parallel computer.
- Had 256 64-bit floating point units (FPUs).
- 4 central processing units (CPUs) were able to process 1 billion operations per seconds.
- Eventually had 16 processors due to cost escalation.
- 1976: Runs first successful application.
- Cost for one machine > 31 million USD (1972)
- Max 50 Floating Point Operations per Second(FLOPS)


G. H. Barnes, R. M. Brown, M. Kato, D. J. Kuck, D. L. Slotnick and R. A. Stokes, "The ILLIAC IV Computer," in *IEEE Transactions on Computers*, vol. C-17, no. 8, pp. 746-757, Aug. 1968, doi: 10.1109/TC.1968.229158.

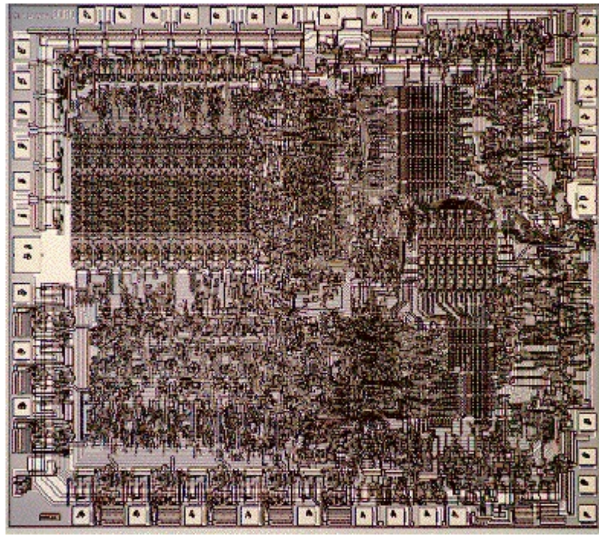


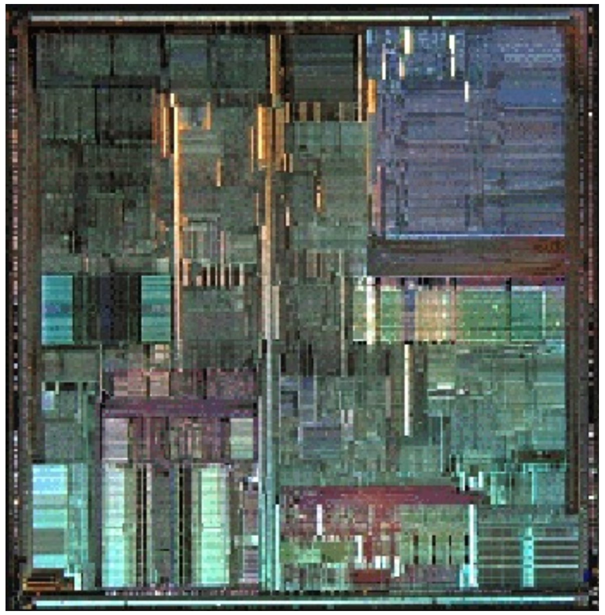
ILLIAC IV Processing Unit and Control Unit
https://en.wikipedia.org/wiki/ILLIAC_IV

PARALLEL COMPUTING

1980-2005: Era of Desktop Computers

- Availability of Uni-processor; cheaper computing!
- Uni-(micro) processors became exponentially faster at running sequential programs
- Traditional doubling of clock speeds every 18–24 months
- Need for parallelism declined
- 2005 -> Reached the limits !
    - Power wall: Increasing clock rate generates too much heat. Power consumption increases
    - Memory wall: Increasing clock rate generates larger gaps in memory-CPU speeds
    - Parallelism wall: Increasingly difficult to write parallel programs to keep the processor busy
    - Cooling constraints limit increases in microprocessor clock speeds


Intel 8080 processor: 1975, 4,500 transistors


Intel Pentium Pro, 1995, 5.5 million transistors

PARALLEL COMPUTING

2005 onwards: Moores Law

- Make wires exponentially smaller
- System-on-Chip (SoC) Design: Multiple components on one Integrated Circuit
- 2007: First Dual core processors in market (Intel, AMD)
- 2008 onwards: Multiple-cores on one SoC
- 2010+, the level of parallelism on a single microprocessor now rivals the number of nodes in the most massively parallel supercomputers of the 1980s
- 2020+, extreme scale High Performance Cluster (HPC) systems are anticipated to have on the order of 100,000–1,000,000 sockets, with each socket containing between 100 and 1000 heterogeneous cores

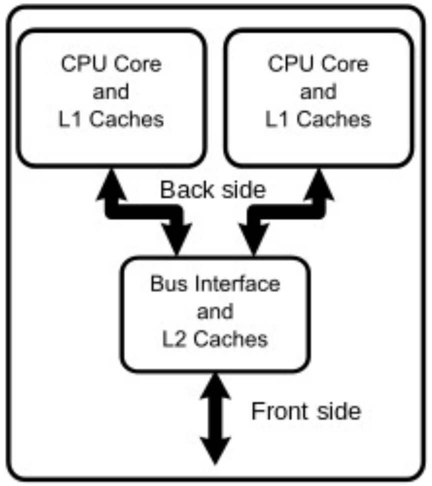
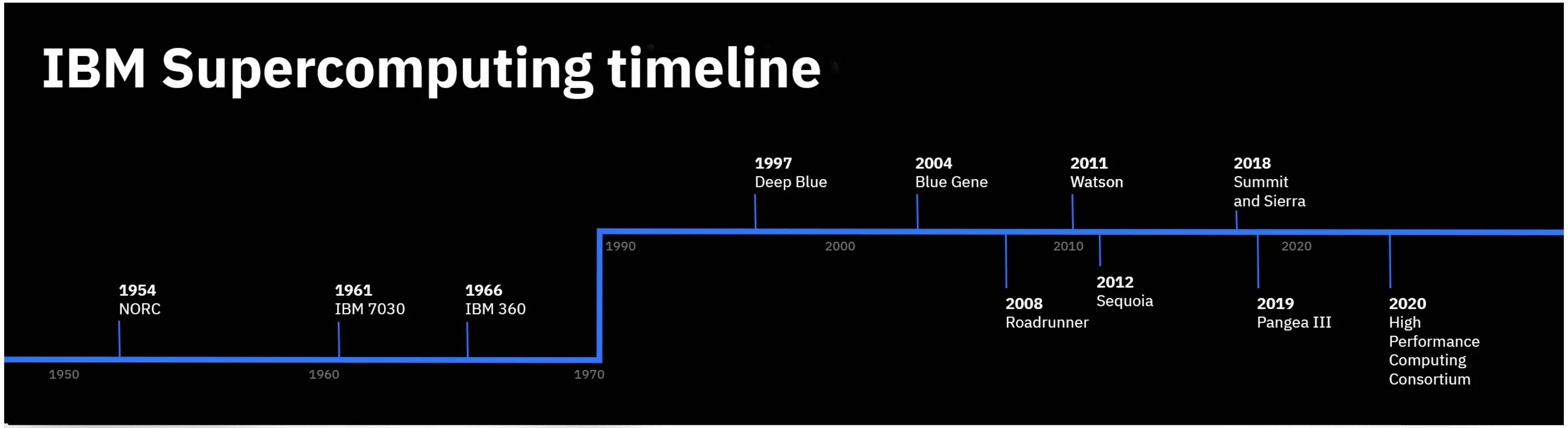


Diagram of a generic dual-core processor

Intel Core 2 Duo, 2007

AMD Athlon X2 6400+, 2007

PARALLEL COMPUTING



1954
The Naval Ordnance Research Calculator helped forecast weather and performed other complex calculations.

1961
The **IBM 7030** was capable of 2 million operations per second.

1966
The **IBM 360** and its successors helped power NASA's Apollo program.

1997
Deep Blue wins its match with chess grandmaster Garry Kasparov.

2004
Blue Gene ushers in a new era of high-performance computing as it helps biologists explore gene development.

2008
Built for Los Alamos National Laboratory, **Roadrunner** is the first super-computer in the world to reach petaflop speed.

2011
Watson beats human competitors on Jeopardy!, earning a million-dollar jackpot for charity.

2012
Sequoia, the third-generation **Blue Gene** system, reaches speeds of 16.32 petaflops.

2018
Summit begins work at Oak Ridge National Laboratory; a sister machine, **Sierra,** launches at Lawrence Livermore National Laboratory.

2019
IBM builds **Pangea III,** the world's most powerful commercial super-computer, for Total to accurately locate new energy resources.

2020
IBM helps launch the COVID-19 **High Performance Computing Consortium** to research the COVID-19 virus and its potential cures.

https://www.ibm.com/topics/supercomputing

PARALLEL COMPUTING

- Performance
  - Supercomputing is measured in floating-point operations per second (FLOPS).
  - Petaflops are a measure of a computer's processing speed equal to a thousand trillion flops.
  - 1-petaflop computer system can perform one quadrillion (10^{15}) flops.
  - Fastest Computer in the world (2020)
    - Fugaku (Kobe-JAPAN)
      - Cores: 7,630,848
      - Max FLOPS: 442.01 PFLOPS or (537,212,000 Giga FLOPs)
      - Power: 29,899 kW

https://www.fujitsu.com/global/about/innovation/fugaku/

https://www.ibm.com/topics/supercomputing

PARALLEL COMPUTING

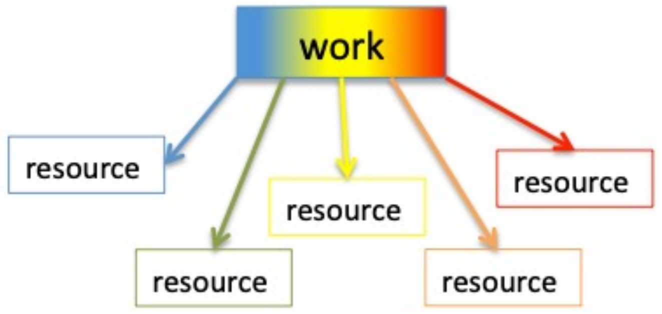
What to do with multi-processors?

- Run multiple totally different programs at the same time
  - Already do that by time-slicing

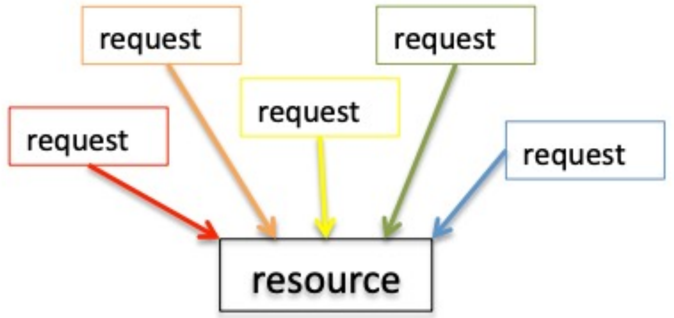
- Do multiple things in ONE program
  - More difficult
  - Need to re-think writing parallel programs
    - Using multiple cores
    - Using Memory
    - Using I/O
    - Using appropraite structures to support parallelism
  - Writing parallel programs (Painful!)
    - Manage complexity, follow principles of parallelism
    - Manage concurrency

PARALLEL COMPUTING

Parallel: Use extra computational resources to solve a problem faster



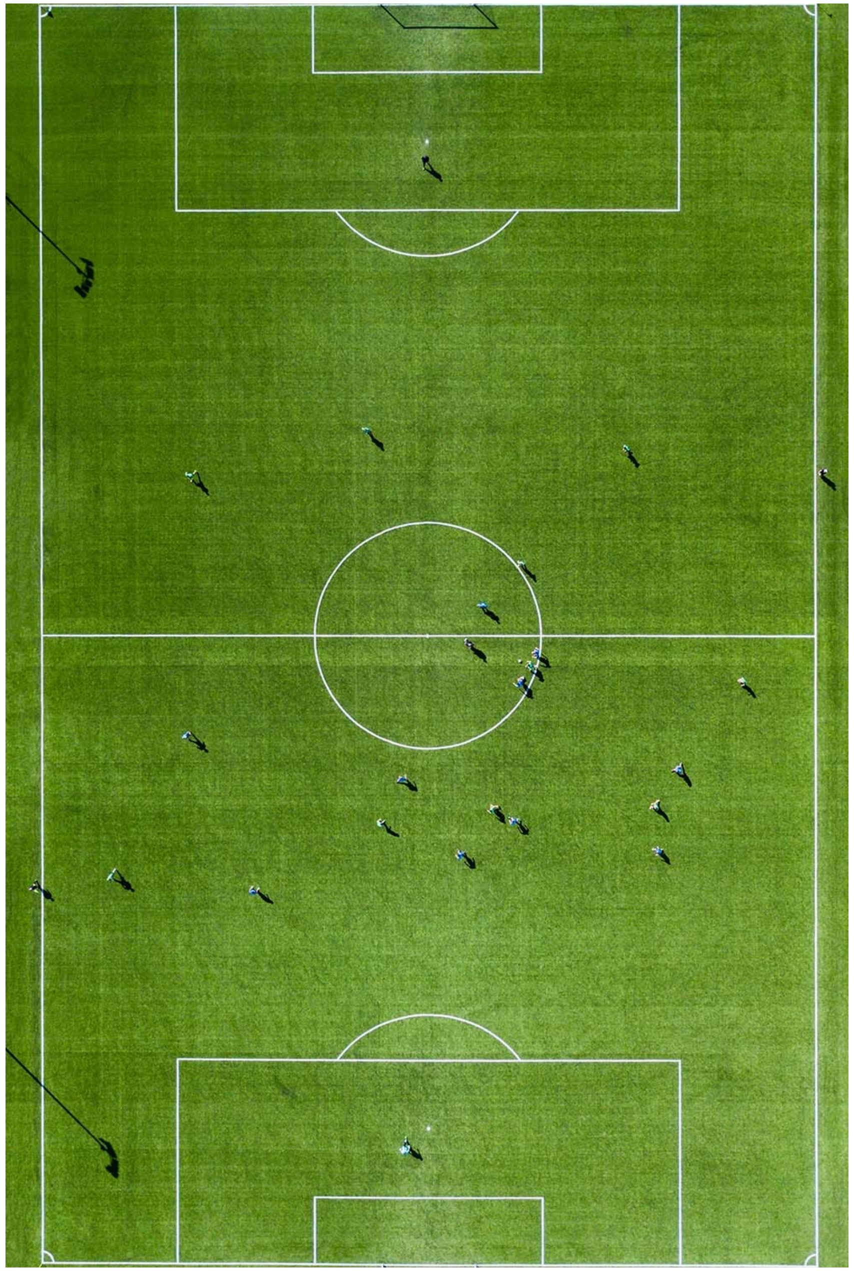
Concurrent: Correctly and efficiently manage access to shared resources



A Sophomoric Introduction to Shared-Memory Parallelism and Concurrency, Dan Grossman, online notes, version Feb 2012

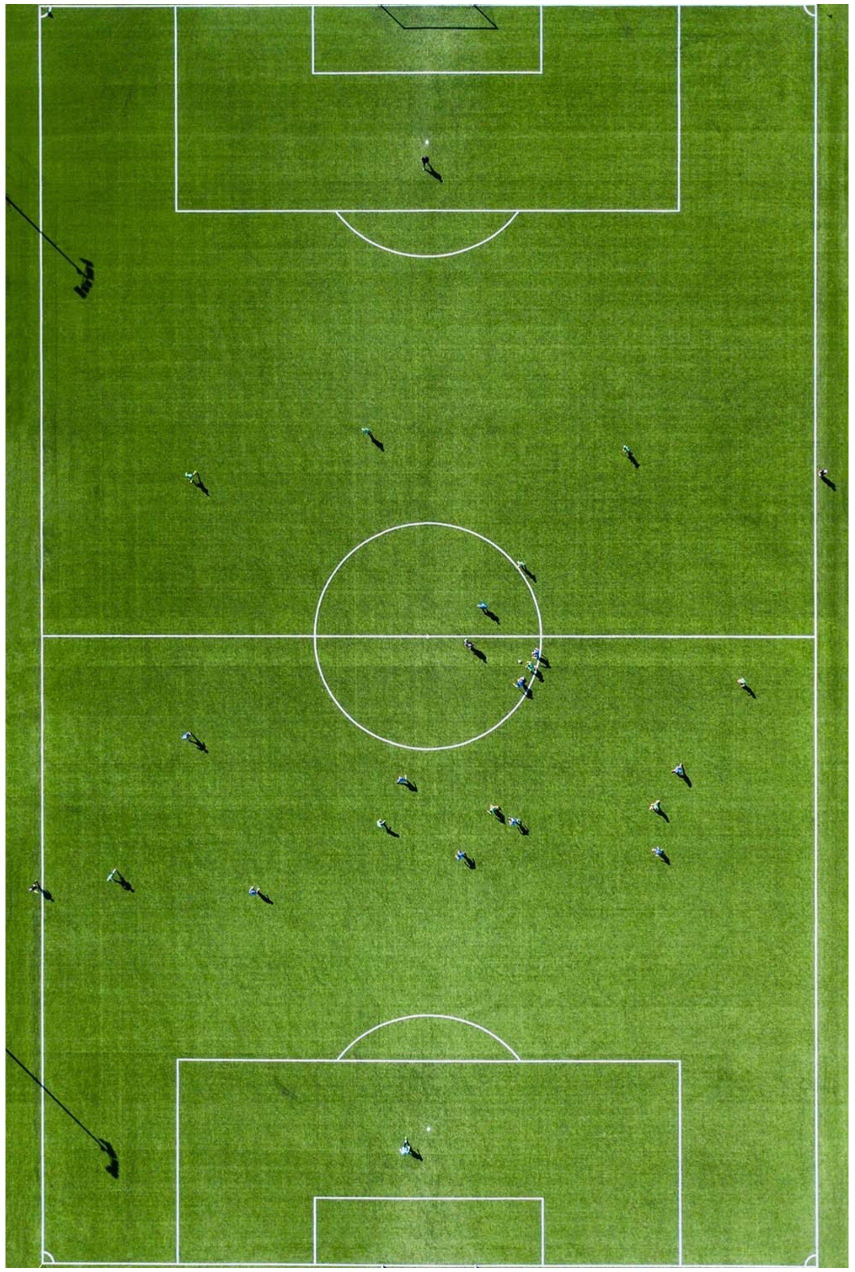
PARALLEL COMPUTING

- Understanding Parallelism with Analogy
- A Serial Program:
  - One player dribbles and scores goal
- A parallel Program:
  - Use a team of 11 players. Each player has a role to play (Goal-keeper, Defender, Midfielder, Forward Striker) [Role decomposition]
  - Assign tasks to each set of players (corner, free-kick, penalty taking, pressing, defending etc) [Task Decomposition]
  - Have extra help/resources e.g. substitutes [work pool]
  - Problem: Coordination!



PARALLEL COMPUTING

- Understanding Concurrency with Analogy
- Concurrency:
  - Too many players on the pitch, but only ONE ball and TWO goal posts.
  - Need to manage the game within game-constraints (90-minute time, half-time etc)
  - Avoid hand-balls, corners, penalty kicks etc



PARALLEL COMPUTING

- In reality: **Parallelism and concurrency are mixed**
  - Common to use threads for both
  - If parallel computations need access to shared resources, then the concurrency needs to be managed
  - Threads, Processes, Mutual Exclusion, Shared memory, Inter-process-communication, etc
  - In this course, we will first cover parallelism and later Concurrency

PARALLEL COMPUTING

- In reality: Parallelism and concurrency is everywhere
  - Operating Systems
  - Real time systems
  - MMPOG games
  - GPU based systems
  - AI/ML based systems
  - ChatGPT
  - Animated Movies: CGI Render Farms

https://sciencebehindpixar.org/pipeline/rendering

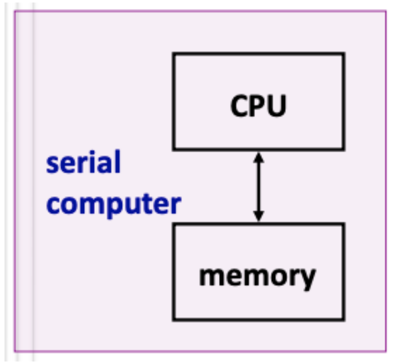
https://www.sabrepc.com/blog/Deep-Learning-and-AI/render-farms-for-cgi

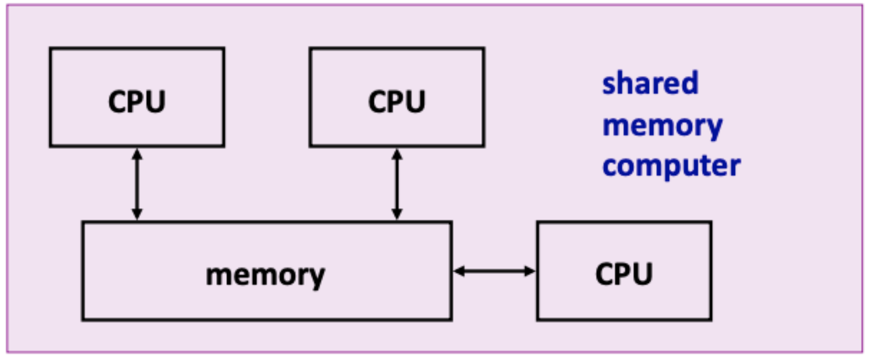
PARALLEL COMPUTING

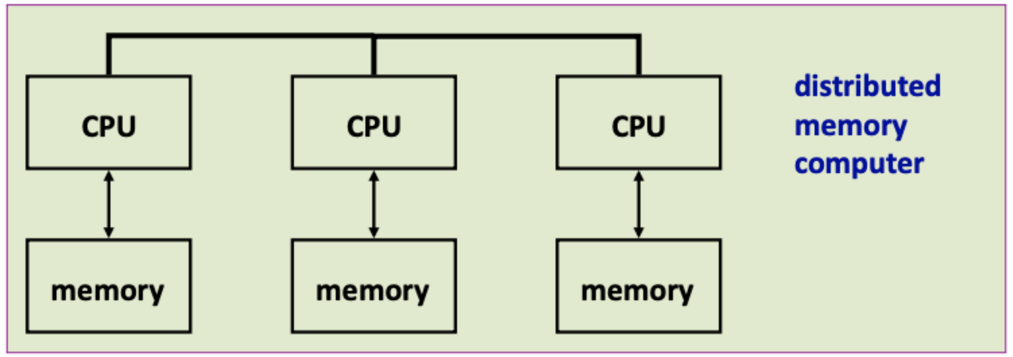
- **So what is a parallel computer?**
  - A computer with a CPU with 2-cores?
  - or A computer with 2 or more CPU each with 2 or more cores?
  - or 2 or more computers with 1 or more multi-core processors?
  - or a computer with a GPU (1200+ cores)?
  - Or multiple computers with many GPUs?
  - Data Center?
  - Cloud?

PARALLEL COMPUTING

- What about Memory Parallelism?
    - Serial Bus connecting memory and processor
    - A shared memory Computer
    - Distributed Memory Computer



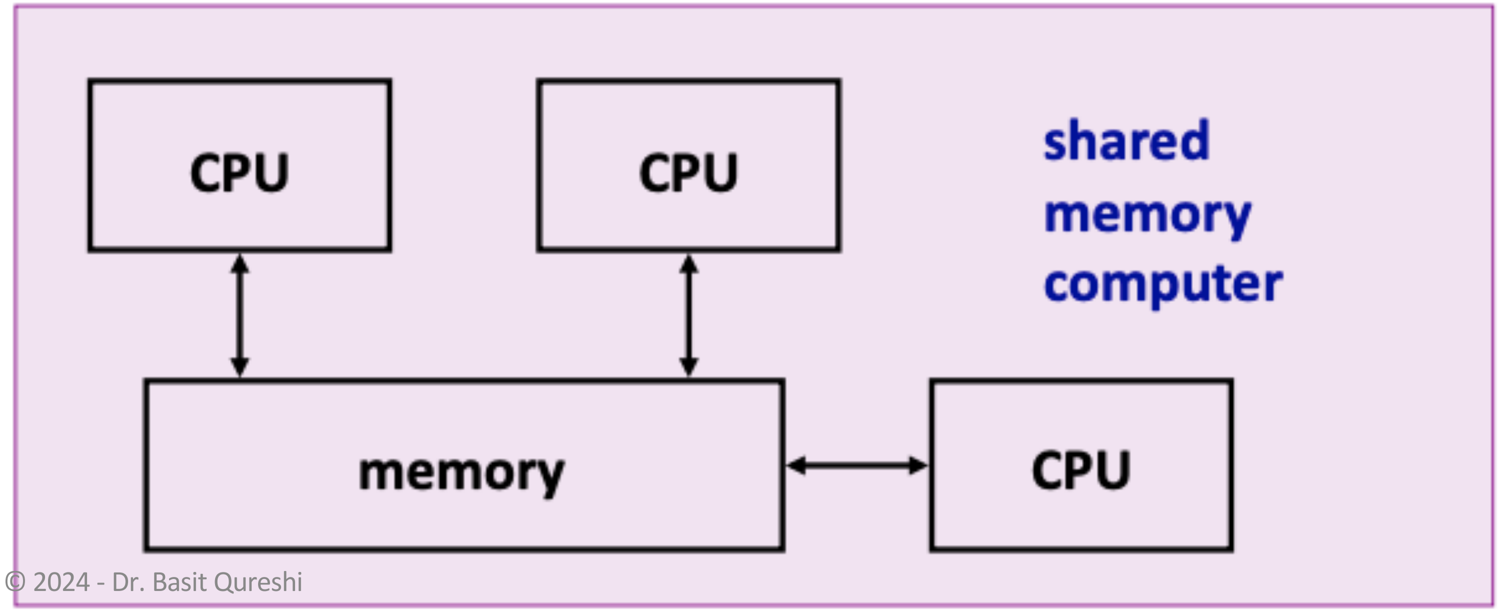




PARALLEL COMPUTING

The Shared Memory Multiprocessor (SMP)

- All memory is placed into a single (physical) address space.
- Processors connected by some form of interconnection network.
- Single virtual address space across all of memory.
- Each processor can access all locations in memory.
- Processes must communicate in order to synchronize or exchange data using the memory space.



PARALLEL PROGRAMMING

PARALLEL PROGRAMMING

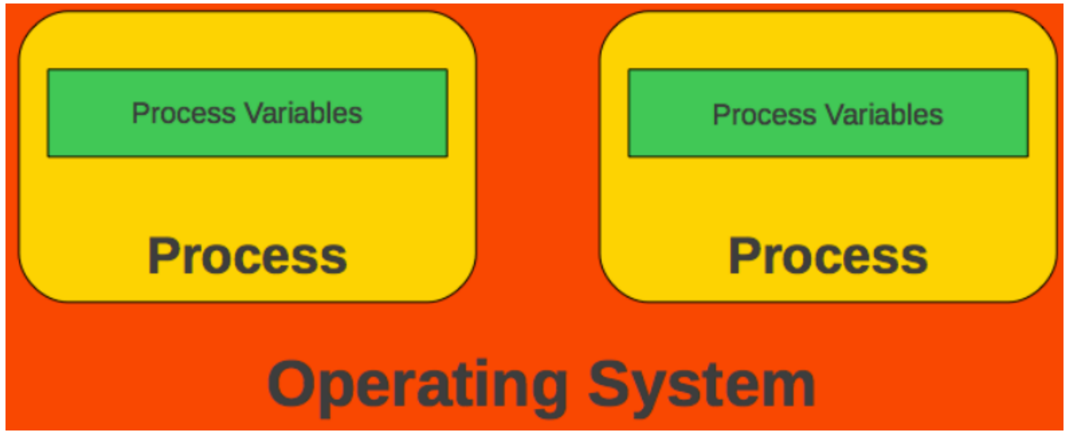
- In recent times, the technology has converged around 3 programming environments:
  - **OpenMP**: simple language extension to C, C++ and Fortran to write parallel programs for shared memory computers (shared memory model)
  - **MPI**: A message-passing library used on clusters and other distributed memory computers (message passing model)
  - **Java language features**: support parallel programming on shared memory computers and standard class libraries supporting distributed computing (shared memory model and message passing model)

PARALLEL PROGRAMMING

- To write a shared-memory parallel program, need new primitives from a programming language or library
  - Threads are ways to create and run multiple things at once.
  - Shared memory can be utilized by threads to share/update data.
  - Synchronize the execution of tasks/primitives using threads.

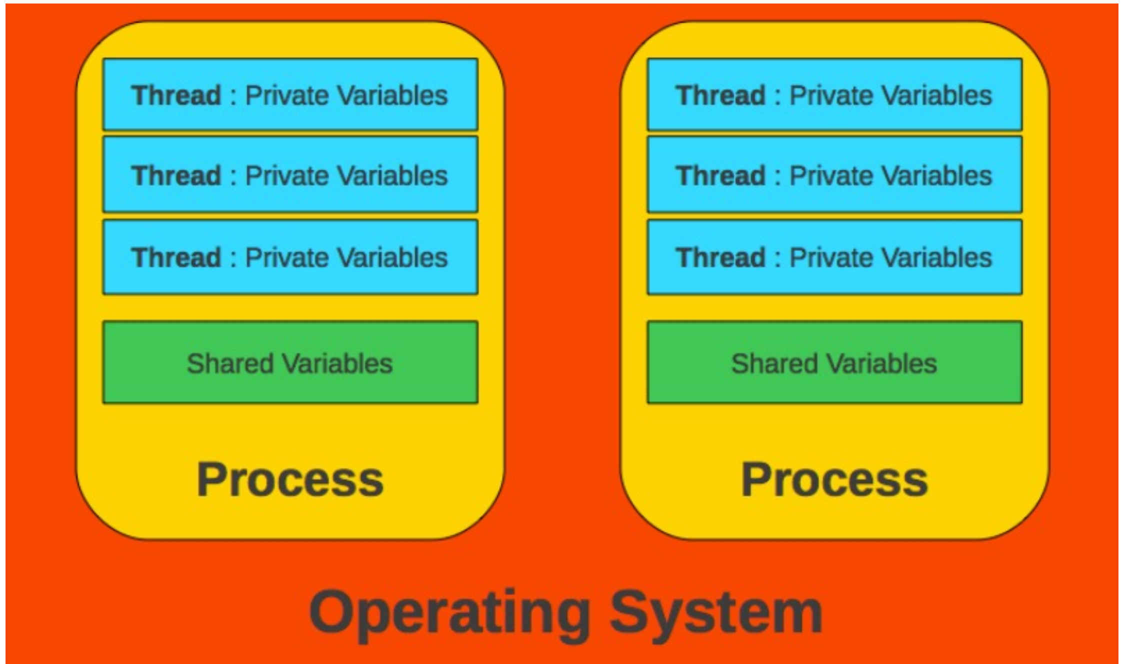
PROCESSES AND THREADS

- Process originates from operating systems.
  - A unit of resource allocation both for CPU time and for memory.
  - A process is represented by its code, data and the state of the machine registers.
  - The data of the process is divided into global variables and local variables, organized as a stack.
  - Generally, each process in an operating system has its own address space and some special action must be taken to allow different processes to access shared data.



PROCESSES AND THREADS

- Thread: The traditional OS process has a single thread of control – it has no internal concurrency.
  - With the advent of shared memory multiprocessors, operating system designers catered for the requirement that a process might require internal concurrency by providing lightweight processes or threads.
  - “thread of control”
  - Modern operating systems permit an operating system process to have multiple threads of control.
  - In order for a process to support multiple (lightweight) threads of control, it has multiple stacks, one for each thread.


Thread : Private Variables
Thread : Private Variables
Thread : Private Variables
Shared Variables
Process
Thread : Private Variables
Thread : Private Variables
Thread : Private Variables
Shared Variables
Process
Operating System

PARALLEL PROGRAM

- A sequential program has a single thread of control
- A parallel program has multiple threads of control
  - Can perform multiple computations in parallel
  - Can control multiple simultaneous external activities
  - Threads from the same process share memory (data and code).
  - They can communicate easily, but it's dangerous if you don't protect your variables correctly.

PARALLEL PROGRAM

- Parallel execution does not require multiple processors

“Interleaving the instructions from multiple processes on a single processor can be used to simulate concurrency, giving the illusion of parallel execution”.

- Pseudo-concurrent execution runs instructions from different processes but are not executed at the same time, but are interleaved.

“it is usual to have more active processes than processors. In this case, the available processes are switched between processors”

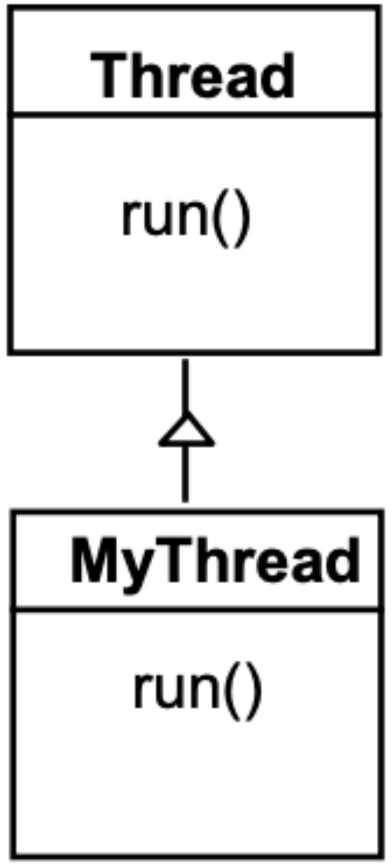
PARALLEL PROGRAM IN JAVA

- Java SE 7 introduced the Fork/Join framework. It was designed to make divide-and-conquer algorithms easy to parallelize

`java.lang.Thread`

- Operations to create and initialize basic threads and control their execution
- The Java Virtual Machine
  - Executes as a process under any operating system
  - Supports multiple threads. Each Java thread has its own local variables organized as a stack and threads can access shared variables.

PARALLEL PROGRAM IN JAVA



- A Thread class manages a single sequential thread of control. Threads may be created and deleted dynamically.
- Thread class executes instructions from its method **run()**.
- The actual code executed depends on the implementation provided for **run()** in a derived class.

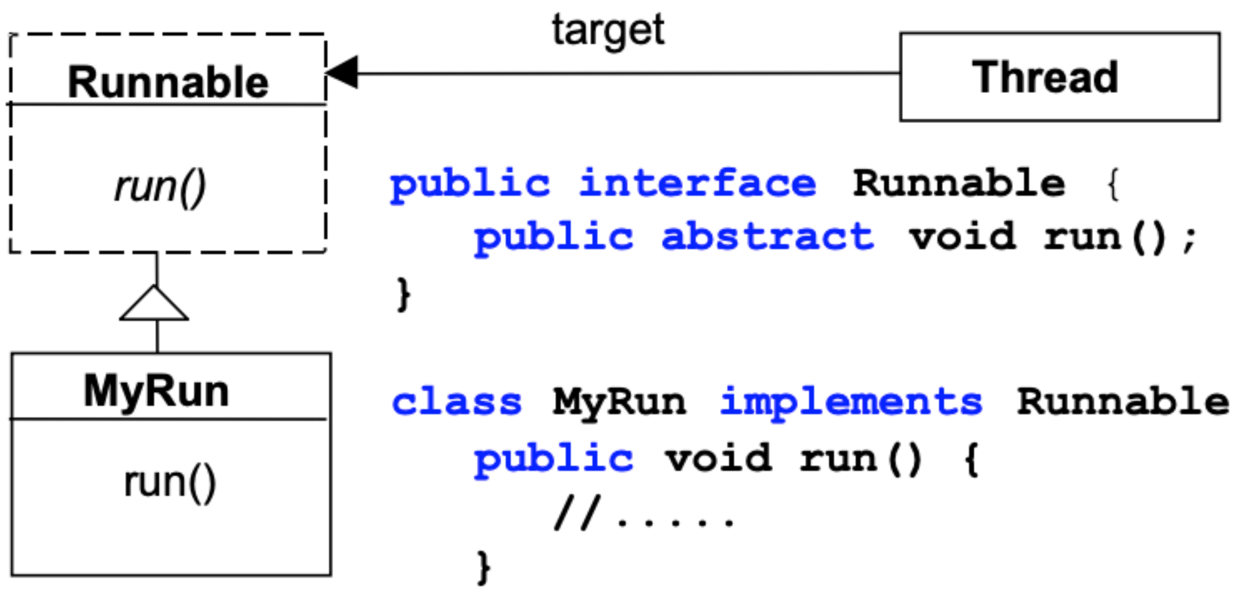
```
class MyThread extends Thread {
    public void run() {
        //......
    }
}
```

Creating a thread object:

```
    Thread a = new MyThread();
```

PARALLEL PROGRAM IN JAVA

Since Java does not permit multiple inheritance, it is sometimes more convenient to implement the **`run()`** method in a class not derived from Thread but from the interface **`Runnable`**



```
public interface Runnable {
    public abstract void run();
}

class MyRun implements Runnable{
    public void run() {
        //.....
    }
}
```

Creating a thread object:

```
        Thread b = new Thread(new MyRun());
```

PARALLEL PROGRAM IN JAVA

- So, there are two ways to create a basic thread in Java:
  - Implement the Runnable interface (`java.lang.Runnable`)
  - Extend the Thread class (`java.lang.Thread`)

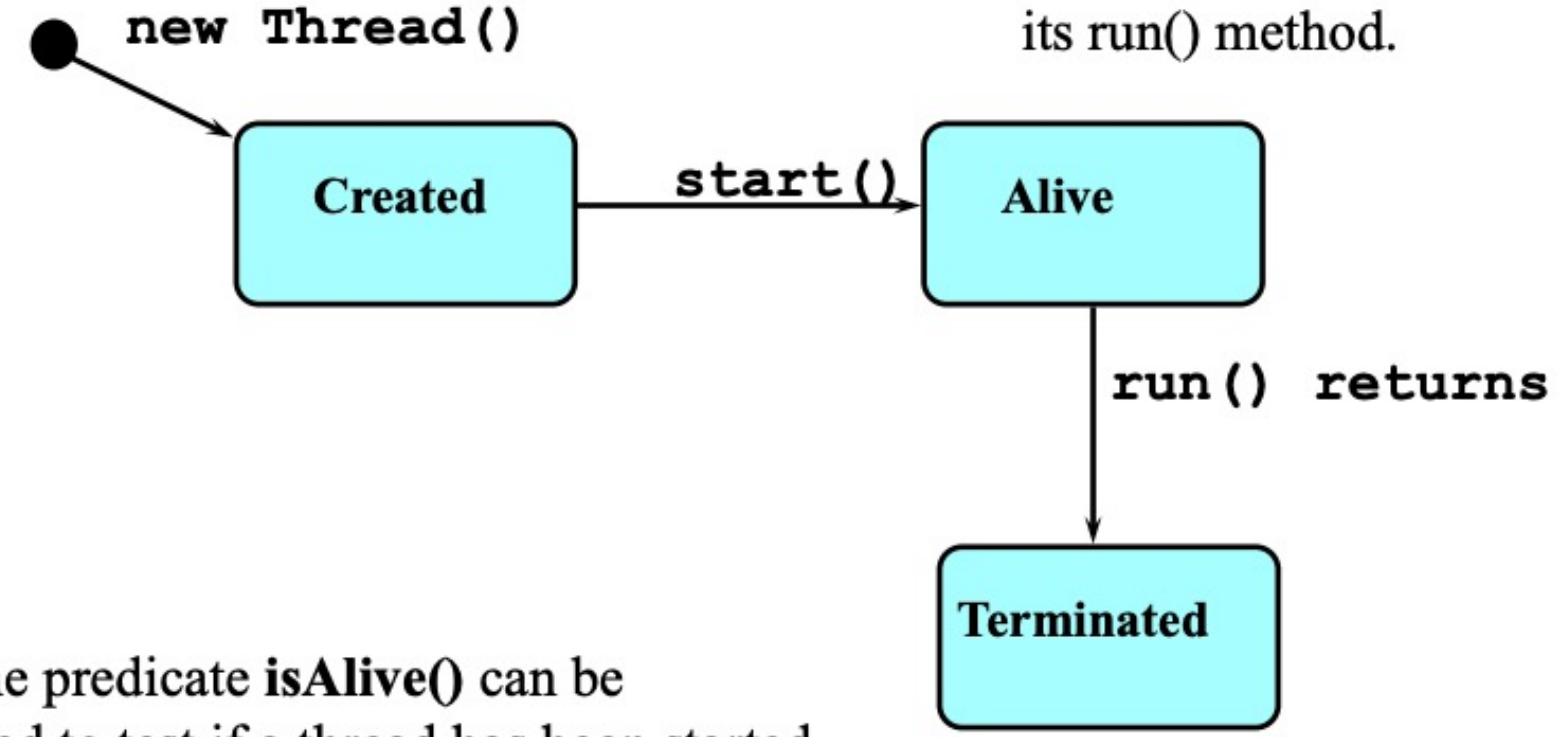
  - Allocation and construction of a Thread object do not cause the thread to run.
  - To get a new thread running:
    - 1. Define a subclass `C` of `java.lang.Thread`, overriding run
    - 2. Create an object of class `C`
    - 3. Call that object's start method
      - Not `run`, which would just be a normal method call
      - `start` sets off a new thread, using run as its "main"

PARALLEL PROGRAM IN JAVA

thread life-cycle in Java

An overview of the life-cycle of a thread as state transitions:

start() causes the thread to call its run() method.

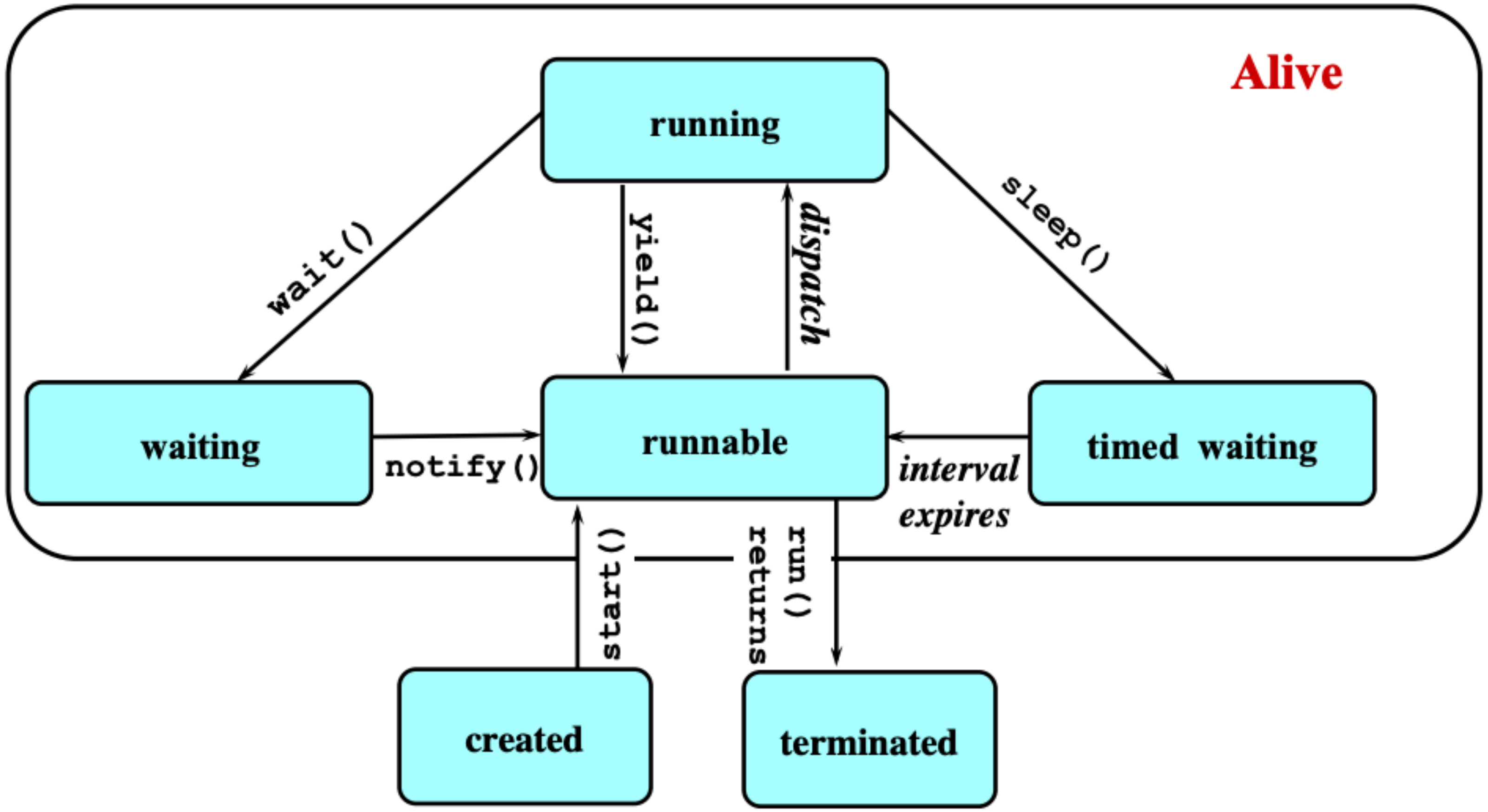


The predicate **isAlive()** can be used to test if a thread has been started but not terminated. Once terminated, it cannot be restarted.

PARALLEL PROGRAM IN JAVA

thread alive states in Java

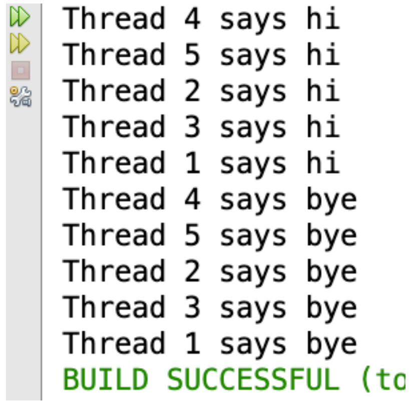
Once started, an **alive** thread has a number of substates :



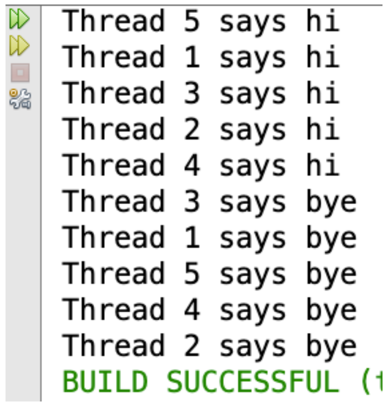
PARALLEL PROGRAM IN JAVA

The following program starts off with one thread and created 3 threads. Look at the output. What gives??

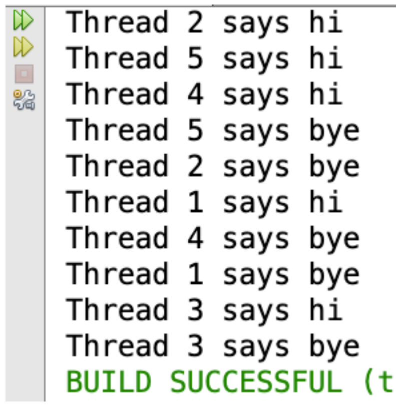
```
class C extends java.lang.Thread {
    int i;
    C(int i) { this.i = i; }
    public void run() {
        System.out.println("Thread " + i + " says hi");
        System.out.println("Thread " + i + " says bye");
    }
}
class M {
    public static void main(String[] args) {
        for(int i=1; i <= 3; ++i) {
            C c = new C(i);
            c.start();
        }
    }
}
```



```
Thread 4 says hi
Thread 5 says hi
Thread 2 says hi
Thread 3 says hi
Thread 1 says hi
Thread 4 says bye
Thread 5 says bye
Thread 2 says bye
Thread 3 says bye
Thread 1 says bye
BUILD SUCCESSFUL (to
```



```
Thread 5 says hi
Thread 1 says hi
Thread 3 says hi
Thread 2 says hi
Thread 4 says hi
Thread 3 says bye
Thread 1 says bye
Thread 5 says bye
Thread 4 says bye
Thread 2 says bye
BUILD SUCCESSFUL (t
```



```
Thread 2 says hi
Thread 5 says hi
Thread 4 says hi
Thread 5 says bye
Thread 2 says bye
Thread 1 says hi
Thread 4 says bye
Thread 1 says bye
Thread 3 says hi
Thread 3 says bye
BUILD SUCCESSFUL (t
```

SHARED MEMORY IN JAVA: A SIMPLE JAVA PROGRAM

The following set of slides are embedded and are based on “A Sophomoric Introduction to Shared-Memory Parallelism and Concurrency”, Dan Grossman, online notes, version Feb 2012

JAVA BASICS

We will first learn some basics built into Java via the provided **`java.lang.Thread`** package

- We will learn a better library for parallel programming

To get a new thread running:

1. Define a subclass **`C`** of **`java.lang.Thread`**,
2. Override the **`run`** method
3. Create an object of class **`C`**
4. Call that object's **`start`** method

`start` sets off a new thread, using **`run`** as its "main"

What if we instead called the **`run`** method of **`C`**?

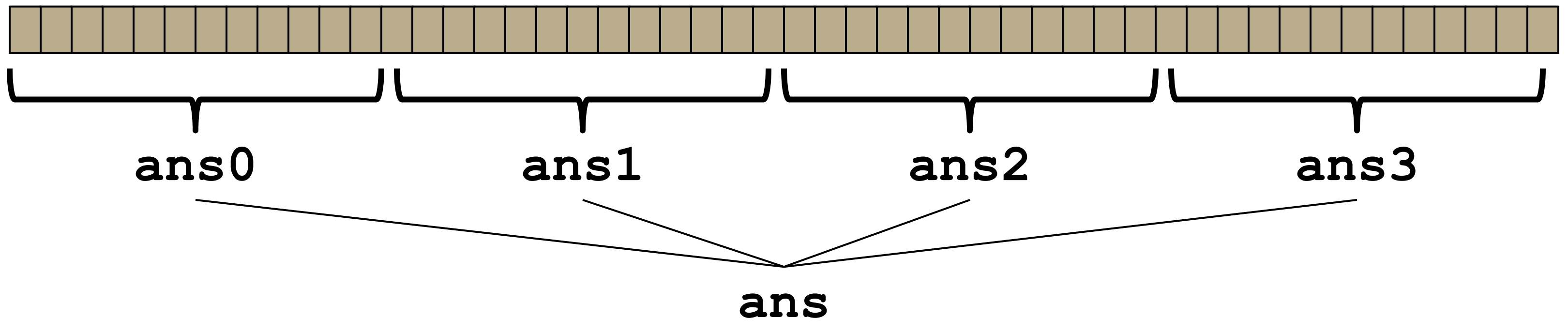
- Just a normal method call in the current thread

PARALLELISM EXAMPLE: SUM AN ARRAY

Have 4 threads simultaneously sum 1/4 of the array

Approach:

- Create 4 thread objects, each given a portion of the work
- Call start() on each thread object to actually run it in parallel
- Somehow ‘wait’ for threads to finish
- Add together their 4 answers for the final result



Warning: This is the inferior first approach, do not do this

CREATING THE THREAD SUBCLASS

```
class SumThread extends java.lang.Thread {

  int lo; // arguments
  int hi;
  int[] arr;

  int ans = 0; // result

  SumThread(int[] a, int l, int h) {
    lo=l; hi=h; arr=a;
  }

  public void run() { //override must have this type
    for(int i=lo; i < hi; i++)
      ans += arr[i];
  }
}
```

We will ignore handling the case where:

arr.length % 4 != 0

Because we override a no-arguments/no-result run, we use fields to communicate data across threads

CREATING THE THREADS WRONGLY

```
class SumThread extends java.lang.Thread {
  int lo, int hi, int[] arr; // arguments
  int ans = 0; // result
  SumThread(int[] a, int l, int h) { … }
  public void run(){ … } // override
}
```

```
int sum(int[] arr){ // can be a static method
  int len = arr.length;
  int ans = 0;
  SumThread[] ts = new SumThread[4];
  for(int i=0; i < 4; i++) // do parallel computations
    ts[i] = new SumThread(arr,i*len/4,(i+1)*len/4);
  for(int i=0; i < 4; i++) // combine results
    ans += ts[i].ans;
  return ans;
}
```

We forgot to start the threads!!!

CREATING THE THREADS WRONGLY

```java
class SumThread extends java.lang.Thread {
  int lo, int hi, int[] arr; // arguments
  int ans = 0; // result
  SumThread(int[] a, int l, int h) { … }
  public void run(){ … } // override
}
```

```java
int sum(int[] arr){ // can be a static method
  int len = arr.length;
  int ans = 0;
  SumThread[] ts = new SumThread[4];
  for(int i=0; i < 4; i++){ // do parallel computations
    ts[i] = new SumThread(arr,i*len/4,(i+1)*len/4);
    ts[i].start(); // start not run
  }
  for(int i=0; i < 4; i++) //
    ans += ts[i].ans;
  return ans;
}
```

We start the threads and then assume they finish right away!!!

JOIN: THE 'WAIT FOR THREAD' METHOD

The **`Thread`** class defines various methods that provide primitive operations you could not implement on your own

- For example: **`start`**, which calls **`run`** in a new thread

The `join` method is another such method, essential for coordination in this kind of computation

- Caller blocks until/unless the receiver is done executing (meaning its **`run`** method returns after its execution)
- Without join, we would have a 'race condition' on **`ts[i].ans`** in which the variable is read/written simultaneously

This style of parallel programming is called `fork/join`"

- If we write in this style, we avoid many concurrency issues
- But certainly not all of them

THIRD ATTEMPT: CORRECT IN SPIRIT

```
int sum(int[] arr){ // can be a static method
  int len = arr.length;
  int ans = 0;
  SumThread[] ts = new SumThread[4];
  for(int i=0; i < 4; i++){// do parallel computations
    ts[i] = new SumThread(arr,i*len/4,(i+1)*len/4);
    ts[i].start();
  }
  for(int i=0; i < 4; i++) { // combine results
    ts[i].join(); // wait for helper to finish!
    ans += ts[i].ans;
  }
  return ans;
}
```

Note that there is no guarantee that ts[0] finishes before ts[1]

- Completion order is nondeterministic
- Not a concern as our threads do the same amount of work

WHERE IS THE SHARED MEMORY?

Fork-join programs tend not to require [thankfully] a lot of focus on sharing memory among threads

- But in languages like Java, there is memory being shared

In our example:

- **`lo`**, **`hi`**, **`arr`** fields written by "main" thread, read by helper thread
- **`ans`** field written by helper thread, read by "main" thread

When using shared memory, the challenge and absolute requirement is to avoid race conditions

- While studying parallelism, we'll stick with **`join`**
- With concurrency, we'll learn other ways to synchronize

BETTER ALGORITHMS: PARALLEL ARRAY SUM

Keep in mind that Java was first released in 1995

A POOR APPROACH: REASONS

Our current array sum code is a poor usage of parallelism for several reasons

1. Code should be reusable and efficient across platforms
   - "Forward-portable" as core count grows
   - At the *very* least, we should parameterize the number of threads used by the algorithm

```
int sum(int[] arr, int numThreads){
  …  // note: shows idea, but has integer-division bug
  int subLen = arr.length / numThreads;
  SumThread[] ts = new SumThread[numThreads];
  for(int i=0; i < numThreads; i++){
   ts[i] = new SumThread(arr,i*subLen,(i+1)*subLen);
   ts[i].start();
  }
  for(int i=0; i < numThreads; i++) {
    …
  }
  …
```

A POOR APPROACH: REASONS

Our current array sum code is a poor usage of parallelism for several reasons

2. We want to use only the processors "available now"
   - Not used by other programs or threads in your program
     - Maybe caller is also using parallelism
     - Available cores can change even while your threads run
   - If 3 processors available and 3 threads would take time **`X`**, creating 4 threads can have worst-case time of **`1.5X`**

```
// numThreads == numProcessors is bad
// if some are needed for other things
int sum(int[] arr, int numThreads){
   …
}
```

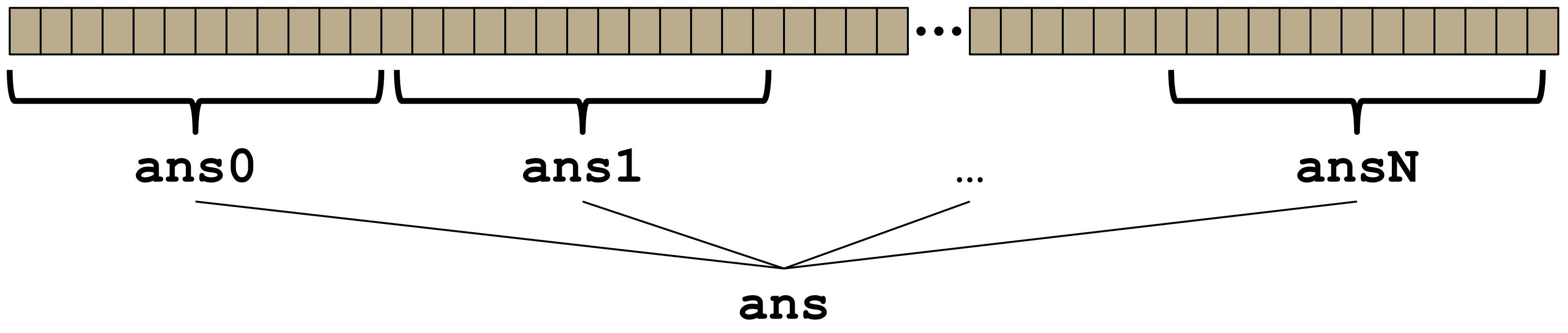
A POOR APPROACH: REASONS

Our current array sum code is a poor usage of parallelism for several reasons

3. Though unlikely for **`sum`**, subproblems may take significantly different amounts of time
   - Example: Apply method **`f`** to every array element, but maybe **`f`** is much slower for some data items
     - Example: Determine if a large integer is prime?
   - If we create 4 threads and all the slow data is processed by 1 of them, we won't get nearly a 4x speedup
     - Example of a load imbalance

A BETTER APPROACH: COUNTERINTUITIVE

Although counterintuitive, the better solution is to use a lot more threads beyond the number of processors



1. **Forward-Portable**: Lots of helpers each doing small work
2. **Processors Available**: Hand out "work chunks" as you go
   - If 3 processors available and have 100 threads, worst-case extra time is < 3% (if we ignore constant factors and load imbalance)
3. **Load Imbalance**: Problem "disappears"
   - Try to ensure that slow threads are scheduled early
   - Variation likely small if pieces of work are also small

BUT DO NOT BE NAÏVE

This approach does not provide a free lunch:

Assume we create 1 thread to process every N elements

```
int sum(int[] arr, int N){
   …
   // How many pieces of size N do we have?
   int numThreads = arr.length / N;
   SumThread[] ts = new SumThread[numThreads];
   …
}
```

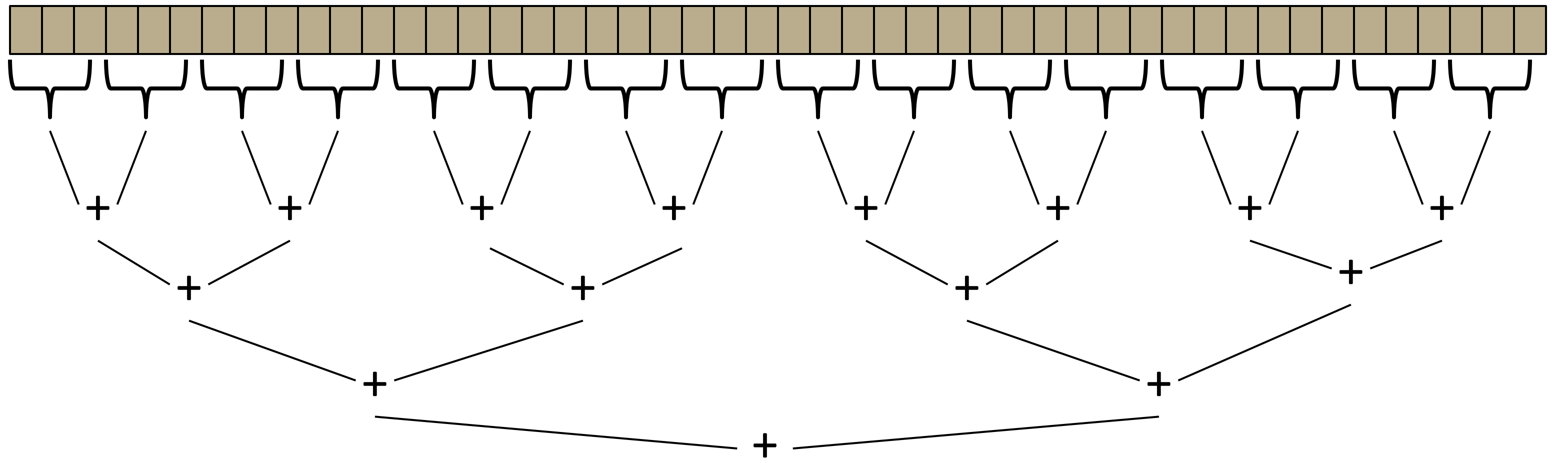
Combining results will require **`arr.length/N`** additions

- As **`N`** increases, this becomes linear in size of array
- Previously we only had 4 pieces, Θ(1) to combine

In the extreme, suppose we create one thread per element

- Using a loop to combine the results requires N iterations

A BETTER IDEA: DIVIDE-AND-CONQUER



Straightforward to implement

Use parallelism for the recursive calls

- Halve and make new thread until size is at some cutoff
- Combine answers in pairs as we return

This starts small but grows threads to fit the problem

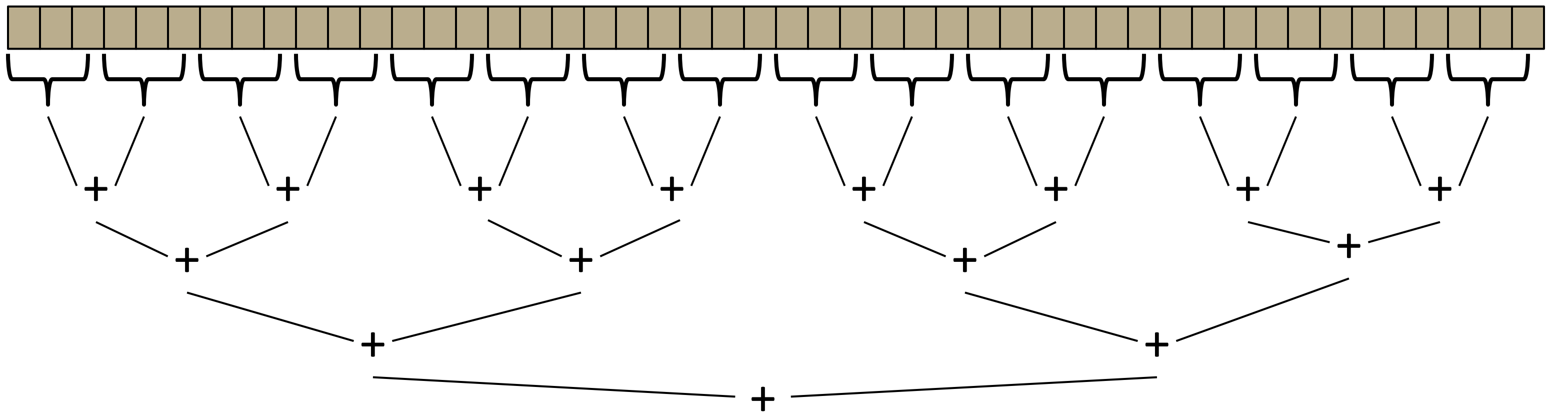
DIVIDE-AND-CONQUER

```
public void run(){ // override
  if(hi - lo < SEQUENTIAL_CUTOFF)
      for(int i=lo; i < hi; i++)
       ans += arr[i];
  else {
    SumThread left = new SumThread(arr,lo,(hi+lo)/2);
    SumThread right= new SumThread(arr,(hi+lo)/2,hi);
    left.start();
→   right.start();                                          ←
    left.join(); // don't move this up a line – why?
    right.join();
    ans = left.ans + right.ans;
  }
 }
}

int sum(int[] arr){
  SumThread t = new SumThread(arr,0,arr.length);
  t.run();
  return t.ans;
}
```

DIVIDE-AND-CONQUER REALLY WORKS

The key is to parallelize the result-combining

- With *enough* processors, total time is the tree height: $O(\log n)$
- This is optimal and exponentially faster than sequential $O(n)$)
- But the reality is that we usually have $P < O(n)$ processors



Still, we will write our parallel algorithms in this style

- Relies on operations being associative (as with +)
- But will use a special library engineered for this style
- It takes care of scheduling the computation well

BEING REALISTIC

In theory, you can divide down to single elements and then do all your result-combining in parallel and get optimal speedup

In practice, creating all those threads and communicating amongst them swamps the savings,

To gain better efficiency:

- Use a *sequential cutoff*, typically around 500-1000
  - Eliminates *almost all* of the recursive thread creation because it eliminates the bottom levels of the tree
  - This is *exactly* like quicksort switching to insertion sort for small subproblems, but even more important here
- Be clever and do not create unneeded threads
  - When creating a thread, you are already in another thread
  - Why not use the current thread to do half the work?
  - Cuts the number of threads created by another 2x

HALVING THE NUMBER OF THREADS

```
// wasteful: don't
SumThread left  = …
SumThread right = …

// create two threads
left.start();
right.start();
left.join();
right.join();
ans=left.ans+right.ans;
```

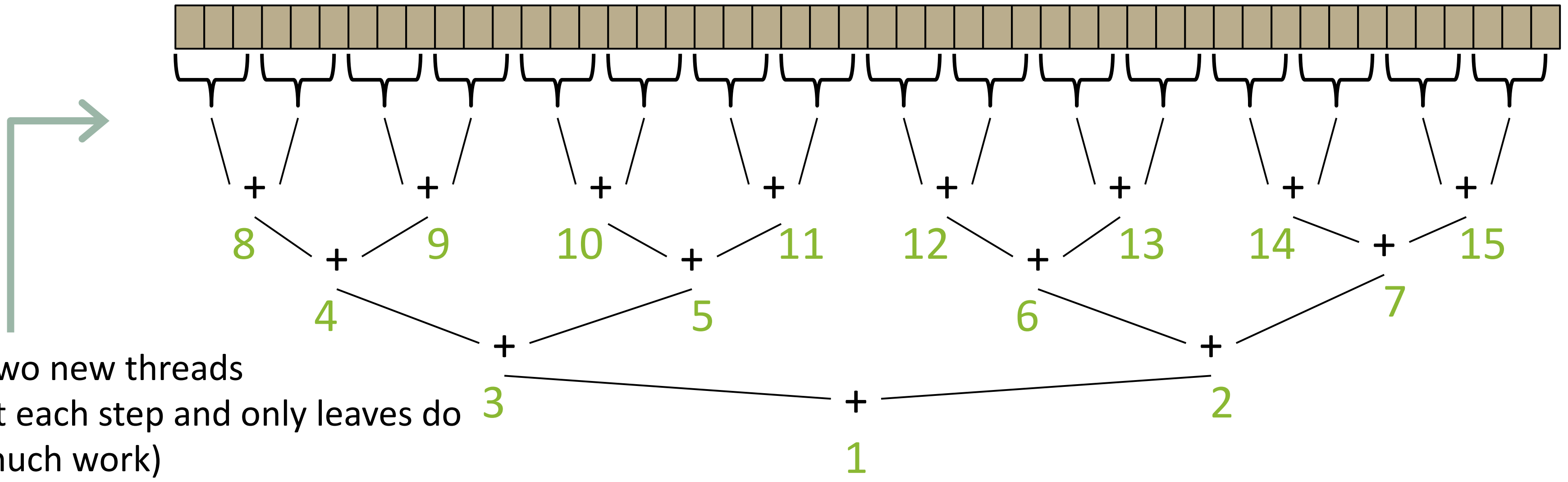
```
// better: do
SumThread left  = …
SumThread right = …

// order of next 4 lines
// essential – why?
left.start();
right.run();
left.join();
ans=left.ans+right.ans;
```

If a *language* had built-in support for fork-join parallelism, we would expect this hand-optimization to be unnecessary

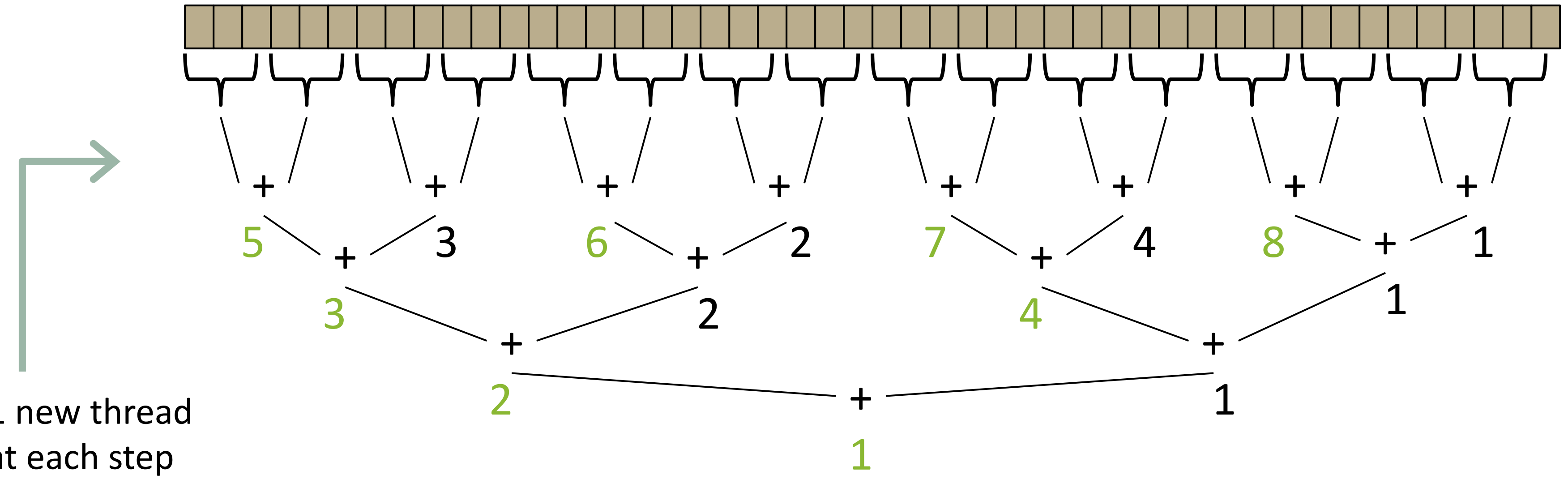
But the *library* we are using expects you to do it yourself

- And the difference is surprisingly substantial
- But no difference in theory

ILLUSTRATION OF FEWER THREADS



Two new threads
at each step and only leaves do
much work)



1 new thread
at each step

LIMITS OF THE JAVA THREAD LIBRARY

Even with all this care, Java's threads are too *heavyweight*

- Constant factors, especially space overhead
- Creating 20,000 Java threads just a bad idea

The ForkJoin Framework is designed/engineered to meet the needs of divide-and-conquer fork-join parallelism

- Included in the Java 7 standard libraries
- Also available as a downloaded **`.jar`** file for Java 6
- Section will discuss some pragmatics/logistics
- Similar libraries available for other languages
  - C/C++: Cilk, Intel's Thread Building Blocks
  - C#: Task Parallel Library
- Library implementation is an advanced topic

DIFFERENT TERMS / SAME BASIC IDEAS

To use the ForkJoin Framework:

- A little standard set-up code (e.g., create a **`ForkJoinPool`**)

The Fundamental Differences:

Don’t subclass **`Thread`**	Do subclass **`RecursiveTask<V>`**
Don’t override **`run`**	Do override **`compute`**
Do not use an **`ans`** field	Do return a **`V`** from **`compute`**
Do not call **`start`**	Do call **`fork`**
Do not just call **`join`**	Do call **`join`** which returns answer
Do not call **`run`** to hand-optimize	Do call **`compute`** to hand-optimize
Do not have a topmost call to **`run`**	Do create a pool and call **`invoke`**

See the Dan Grossman's web page for

"A Beginner’s Introduction to the ForkJoin Framework"

http://www.cs.washington.edu/homes/djg/teachingMaterials/spac/grossmanSPAC_forkJoinFramework.html

FINAL VERSION IN FORKJOIN FRAMEWORK

```
class SumArray extends RecursiveTask<Integer> {
  int lo; int hi; int[] arr; // arguments
  SumArray(int[] a, int l, int h) { … }
  protected Integer compute(){// return answer
    if(hi – lo < SEQUENTIAL_CUTOFF) {
      int ans = 0;
      for(int i=lo; i < hi; i++)
        ans += arr[i];
      return ans;
    } else {
      SumArray left = new SumArray(arr,lo,(hi+lo)/2);
      SumArray right= new SumArray(arr,(hi+lo)/2,hi);
      left.fork();
      int rightAns = right.compute();
      int leftAns  = left.join();
      return leftAns + rightAns;
    }
  }
}

static final ForkJoinPool fjPool = new ForkJoinPool();

int sum(int[] arr){
  return fjPool.invoke(new SumArray(arr,0,arr.length));
}
```

FOR COMPARISON: JAVA THREADS VERSION

```
class SumThread extends java.lang.Thread {
  int lo; int hi; int[] arr;//fields to know what to do
  int ans = 0; // for communicating result
  SumThread(int[] a, int l, int h) { … }
  public void run(){
    if(hi – lo < SEQUENTIAL_CUTOFF)
      for(int i=lo; i < hi; i++)
        ans += arr[i];
    else { // create 2 threads, each will do ½ the work
      SumThread left = new SumThread(arr,lo,(hi+lo)/2);
      SumThread right= new SumThread(arr,(hi+lo)/2,hi);
      left.start();
      right.start();
      left.join(); // don't move this up a line – why?
      right.join();
      ans = left.ans + right.ans;
    }
  }
}

class C {
 static int sum(int[] arr){
   SumThread t = new SumThread(arr,0,arr.length);
   t.run(); // only creates one thread
   return t.ans;
 }
}
```

GETTING GOOD RESULTS WITH FORKJOIN

Sequential threshold

- Library documentation recommends doing approximately 100-5000 basic operations in each "piece" of your algorithm

Library needs to "warm up"

- May see slow results before the Java virtual machine re-optimizes the library internals
- When evaluating speed, loop computations to see the "long-term benefit" after these optimizations have occurred

Wait until your computer has more processors

- Seriously, overhead may dominate at 4 processors
- But parallel programming becoming much more important

Beware memory-hierarchy issues

- Will not focus on but can be crucial for parallel performance

SUMMARY

- Writing parallel programs increases the processing speed, but does it??!!
- Threads implement parallelism using shared memory and multi-processors on the same machine.
- Distributed System: Extend the concept to Clusters housing multiple machines