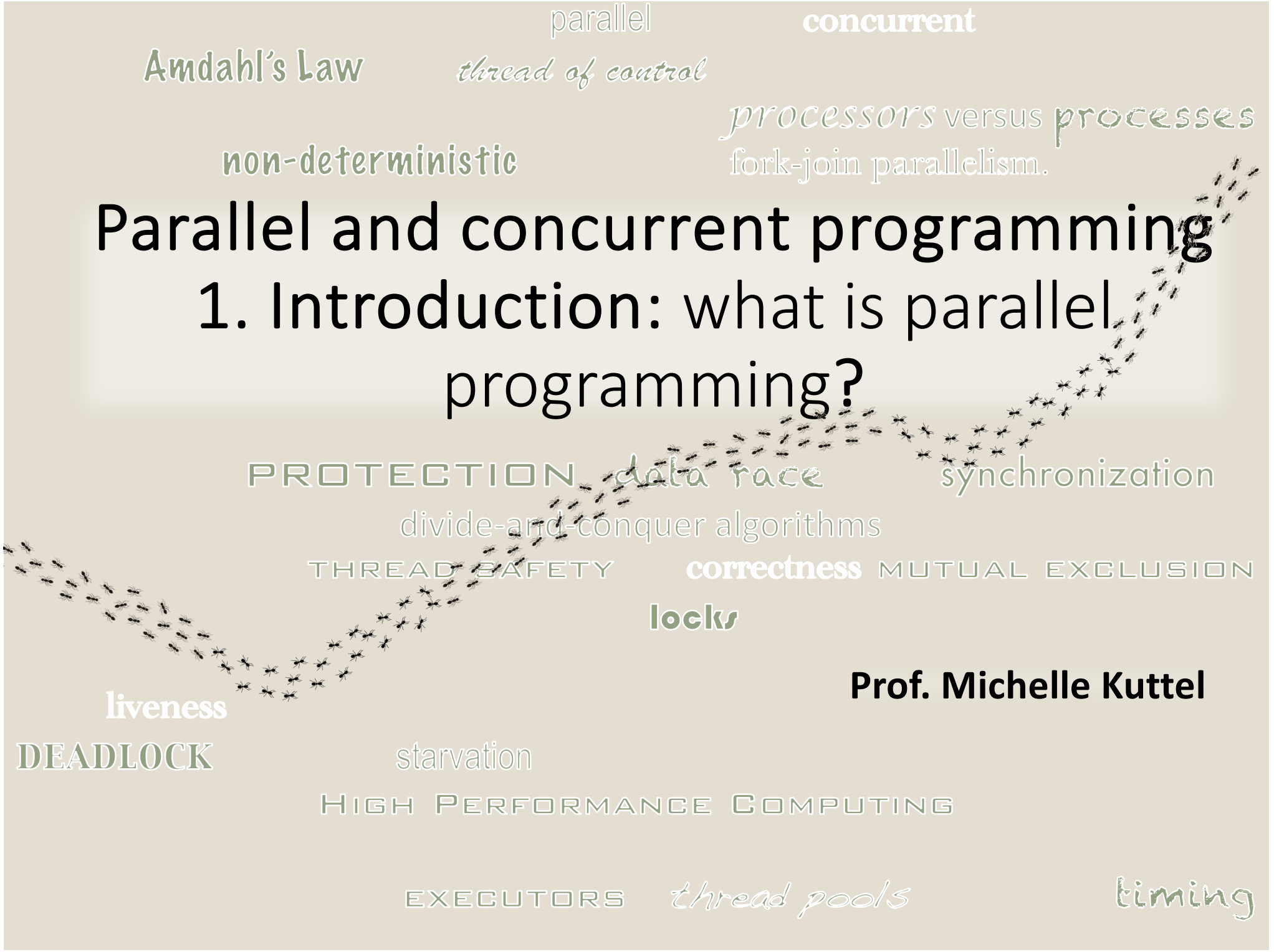
Do PCP 2025 class quiz #1 **now**

On Amathuba

- Password: **serial**


parallel
concurrent
Amdahl's Law
thread of control
processors versus processes
non-deterministic
fork-join parallelism.
Parallel and concurrent programming
1. Introduction: what is parallel programming?
PROTECTION
data race
synchronization
divide-and-conquer algorithms
THREAD SAFETY
correctness
MUTUAL EXCLUSION
locks
Prof. Michelle Kuttel
liveness
DEADLOCK
starvation
HIGH PERFORMANCE COMPUTING
EXECUTORS
thread pools
timing

Who am I?

HOD

Main research focus is **computational glycochemistry**:

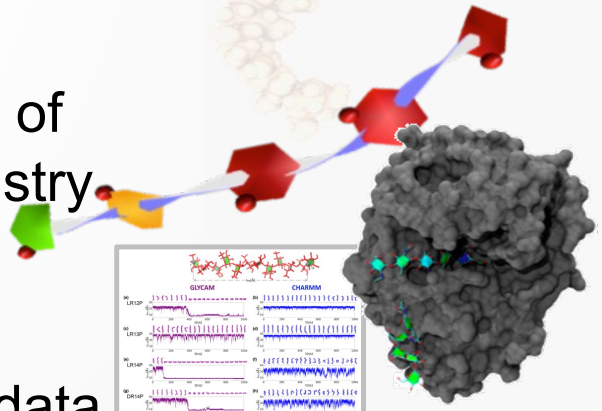
- using molecular modeling to investigate the **conformation** and interactions of bacterial **carbohydrates** that are used in modern **vaccines**

Some other areas:

- **Parallel and High Performance Computing**: using parallel architectures to accelerate compute-intensive algorithms;

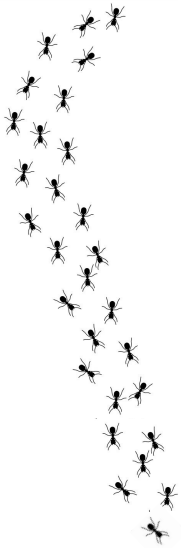
arb uilder

- **Research Programming**: the development of software tools to support research in Chemistry



- **Visualization:** developing novel effective visualizations of complex multidimensional data.

PCP admin



When possible (*loadshedding?!*), course will be filmed for your convenience

- But – you are **required to come to lectures**
- I will be running the **marked quizzes** in most **lectures**.

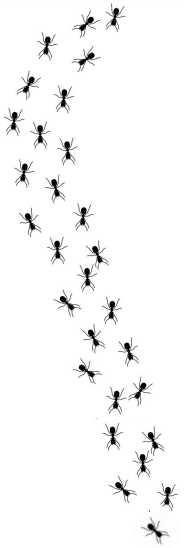
Protocol for course queries for PCP.

•**All general queries** on **Amathuba** or the **CSC2002S MSTeam**.

•If you need speak to **me**, do so before or after class, or make an appointment on the Google appointment booking page: https://calendar.app.google/PWueVvA7xzTy5jNT9

•You **cannot** simply **pop in** at other times**.**

Time management and your PCP assignments



- Historically, **most DPRs** are because students did not submit a PCP assignment.
  - You have to do the assignments,
  - and you have to hand in on time
    - we are not lenient about this.

- These assignments are hard and long (and fun!)
  - **start as soon as they are released**.

- If you have *bad time management*, now is the time to address this *critical weakness*…

PCP Content

This module covers the **essential concepts** of **parallelism** and *concurrency*.

The PCP module will cover 10 sections over the 4 weeks that it runs.

Part I is primary concerned with parallel programming, Part II with concurrency.

(Slides *will be added before the lectures)*

Sections

1. **Introduction:** What is parallel /concurrent programming?
2. **Introduction:** The shared memory programming model
3. **Introduction:** Multithreading in Java
4. Part I: Parallel programming in Java
5. Part I: Parallel programming: algorithms
6. Part I: Parallel programming: performance
7. Part II: Concurrent correctness: Mutual Exclusion
8. Part II: Concurrent correctness: Thread Safety
9. Part II: Concurrent correctness: Condition variables
10. Part II: Concurrent liveness: Deadlock

PCP content

A Sophomoric Introduction to Shared-Memory Parallelism and Concurrency

by Dan Grossman (U. Washington, USA)

This course textbook is **free** and available on Vula

(and a bit *old*, but still valid)

The module will contain other information from other sources; **all content presented online or in class** is **examinable**.

Note also that there will be some changes in content from previous years.

Changing a core assumption

So far, your algorithms/programs have assumed that

one thing happens at a time

this is traditional *sequential programming.*

This slide adapted from: Sophomoric Parallelism and Concurrency, Lecture 1, Dan Grossman

Changing a core assumption

So far, your algorithms/programs have assumed that

one thing happens at a time

this is traditional *sequential programming.*

Everything is part of **one** *sequence*

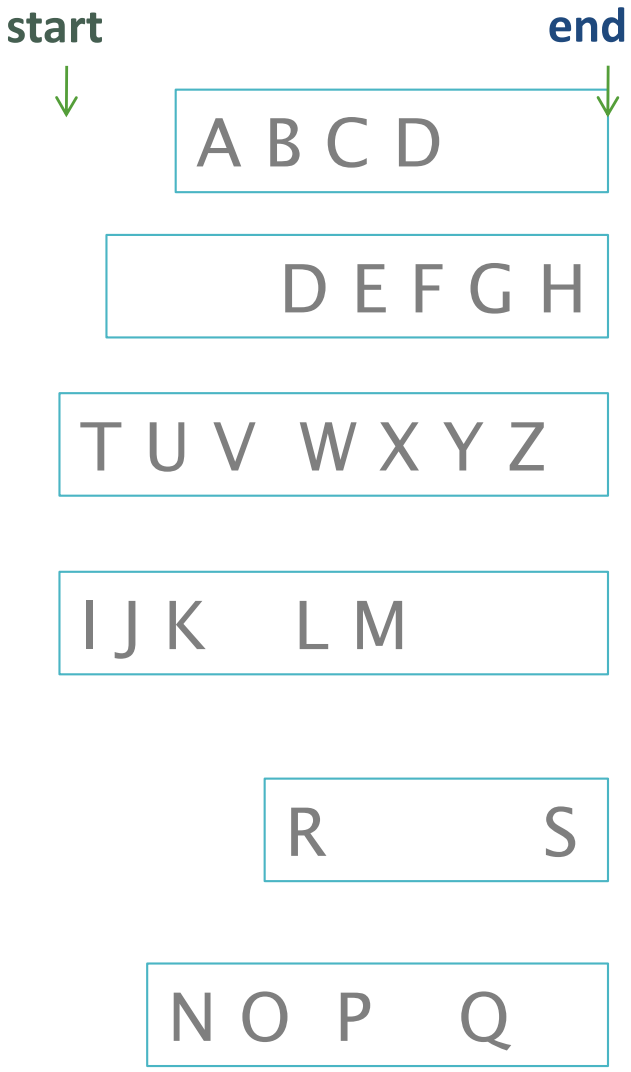
- execution **starts at the beginning** and proceeds one `assignment/call/return/arithmetic operation` at a time

This slide adapted from: Sophomoric Parallelism and Concurrency, Lecture 1, Dan Grossman

Changing a core assumption

We now **remove** the **sequential** assumption and allow

many things to happen **at once**.



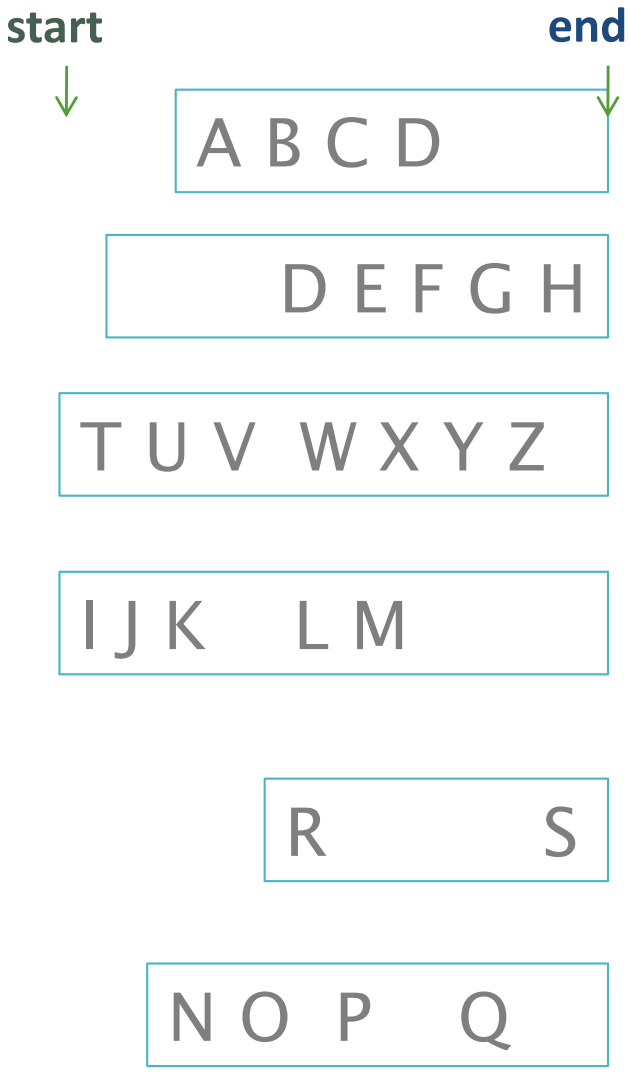
This slide adapted from: Sophomoric Parallelism and Concurrency, Lecture 1, Dan Grossman

Changing a core assumption

We now remove the sequential assumption and allow

many things to **happen at once**.

This **complicates** things…



This slide adapted from: Sophomoric Parallelism and Concurrency, Lecture 1, Dan Grossman

Changing a core assumption

- Parallel and concurrent programming removes the restrictions of sequential programming that require **computational steps** to occur in a **serial order** in **a single place.**

From the ACM/IEEE/AAAI Computer Science curriculum recommendations

In most conventional usage,

- "**parallel**" programming focuses on arranging that **multiple activities co-occur**,
- "**distributed**" programming focuses on arranging that **activities occur in different places**, and
- "**concurrent**" programming focuses on **interactions of** ongoing **activities** with each other and the environment.

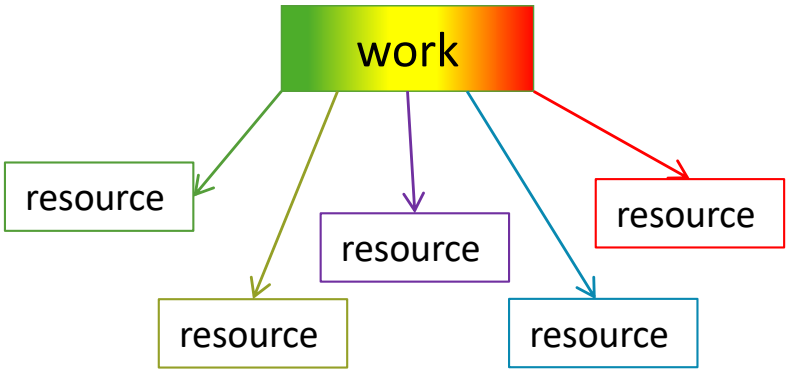
However, **all three** terms may apply in most contexts.

e.g. Parallelism generally implies some form of distribution because multiple activities occurring without sequential ordering constraints happen in multiple physical places.

Parallellism versus *Concurrency*

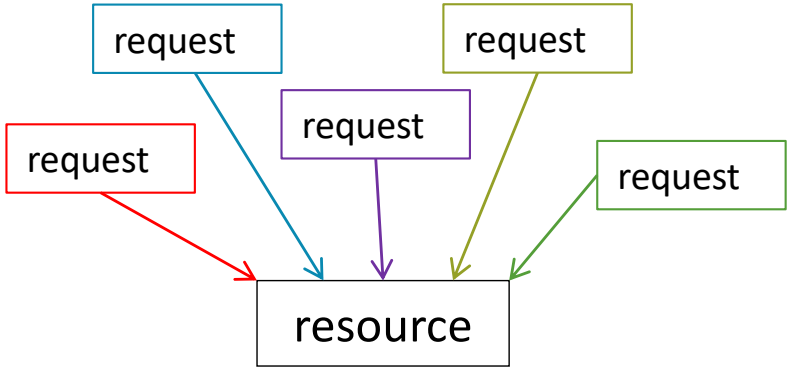
Parallel program:

- Use extra computational resources to solve a problem faster



Concurrent program:

- Correctly and efficiently manage access to shared resources



These terms are NOT standard, but perspective is important.
Many programmers confuse these terms.

Slide adapted from: A Sophomoric Introduction to Shared-Memory Parallelism and Concurrency, Dan Grossman, online notes

Parallel algorithm example

Use **extra computational resources** to solve a problem **faster** (increasing throughput via simultaneous execution)

Pseudocode for array sum

- Bad style for reasons we'll see, but may get roughly 4x speedup

```
int sum(int[] arr){
  res = new int[4];
  len = arr.length;
  FORALL(i=0; i < 4; i++) { //parallel iterations
    res[i] = sumRange(arr,i*len/4,(i+1)*len/4);
  }
  return res[0]+res[1]+res[2]+res[3];
}
int sumRange(int[] arr, int lo, int hi) {
   result = 0;
   for(j=lo; j < hi; j++)
      result += arr[j];
   return result;
}
```

A pseudocode FORALL loop is like a *for* loop, except that it does all the iterations in parallel (**at once**).

This slide adapted from: Sophomoric Parallelism and Concurrency, Dan Grossman

Concurrency Example

Multiple operations on **hash table**

- What happens if two **inserts** at same time?

  Duplicate key?

- We need to **prevent this**.

Concurrency Example

Concurrency: Correctly and efficiently **manage access** to **shared resources** (from multiple possibly-simultaneous clients)

Pseudocode for a **shared hashtable**

- Prevent *bad interleaving* (correctness)
- But allow some concurrent access (performance)

```
class Hashtable<K,V> {
    …
    void insert(K key, V value) {
        int bucket = …;
        prevent-other-inserts/lookups in table[bucket]
        do the insertion
        re-enable access to arr[bucket]
    }
    V lookup(K key) {
        (like insert, but can allow concurrent
         lookups to same bucket)
    }
}
```

concurrent programs use **synchronization** to prevent multiple operations from interleaving in a way that leads to incorrect results

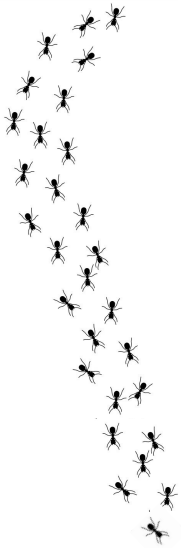
This slide adapted from: Sophomoric Parallelism and Concurrency, Lecture 1, Dan Grossman

Summary: Changing a core assumption

Removing the sequential assumption creates both **opportunities** and **challenges**

- Programming:
  - **Divide** and **coordinate work**
- Algorithms:
  - more **throughput**: work done per unit wall-clock time = speedup
  - more **organization required**
- Data structures:
  - May need to support **concurrent access**

Parallelism versus Concurrency

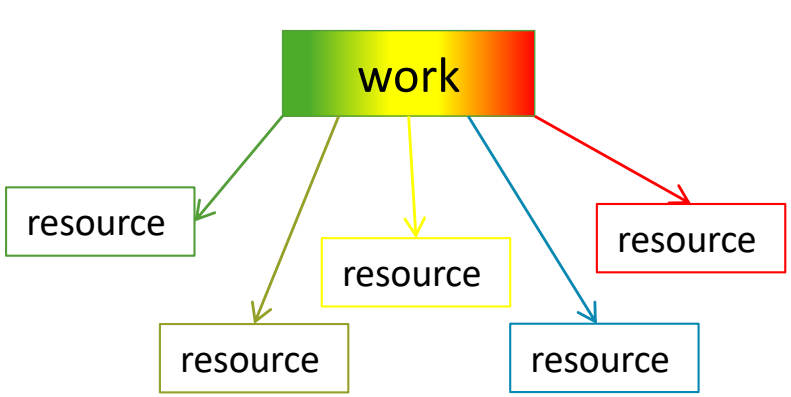


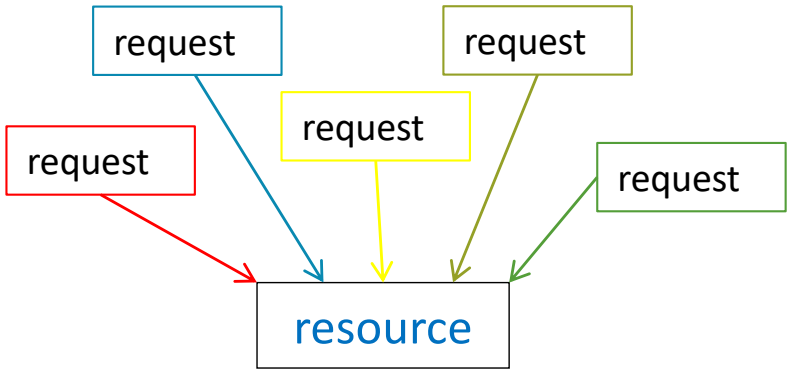
There is some connection:

- If parallel computations need access to shared resources, then the concurrency needs to be managed

We first cover **parallelism**, then *concurrency*:

one assignment in each



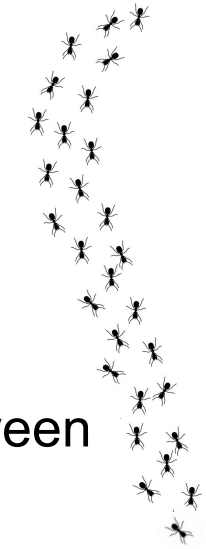


*A Sophomoric Introduction to Shared-Memory Parallelism and Concurrency, Dan Grossman, online notes, version Feb 2012

Why is Parallel/Concurrent Programming Hard?

- Try preparing a seven-course banquet for 300 people
  - by yourself…
  - with one friend….
  - with 32 friends …
  - with 1024 friends.

Restaurant analogy contd.



A serial program is a recipe for **one cook**

- the cook does one thing at a time (sequential), maybe switching between tasks (time-slicing)

Options for **lots of cooks:**

- use helpers to assist with a big task, like slicing lots of potatoes for hot chips (**parallel**)
- dedicate helpers to different tasks, such as beating eggs, slicing onions, washing up (**concurrent**)
- have a list of tasks and assign them to workers as they are free (parallel/concurrent **work pool**)

But…. **too many chefs** = **too much time coordinating**, bumping into each other etc!

Why is Parallel/Concurrent Programming so Hard?

Often there are **multiple steps** that can be done at the same time - with access to more cooks.

- More cooks require **extra coordination**.
  - A cook may have to wait for another cook to finish something.
- And there are **limited resources**:
  - If you have only one oven, two cooks won't be able to bake cakes at different temperatures at the same time.
  - And some recipes will require exclusive use of the oven (e.g. a souffle)

- Multiple cooks present efficiency opportunities, but also **significantly complicate** the process of producing a meal.

Restaurant analogy contd.

Timing (*concurrency*) issues

- Lots of cooks making different things, but only 2 ovens
  - One approach is to allow access to ovens but only for one cake at a time (for safety, cakes can flop)
  - Cooks **must wait** until oven free

Do PCP 2025 class quiz #2 **now**

On Amathuba

- Password: **parallel**

Restaurant analogy contd.

Timing (*concurrency*) issues

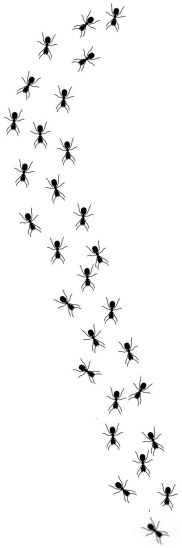
- Lots of cooks making different things, but only 2 ovens
  - One approach is to allow access to ovens but only for one cake at a time (for safety)
  - Cooks **must wait** until oven free

```
if (!ovenBusyLightOn) {
        ovenBusyLightOn=true;
        bakeCake();
        ovenBusyLightOn=false;
}
```

This pseudo code is fine for a single threaded program.

Will it work in a **multithreaded program?**

Restaurant analogy contd.



Timing (*concurrency*) issues

- Lots of cooks making different things, but only 2 ovens
  - One approach is to allow access to ovens but only for one cake at a time (for safety)
  - Cooks **must wait** until oven free

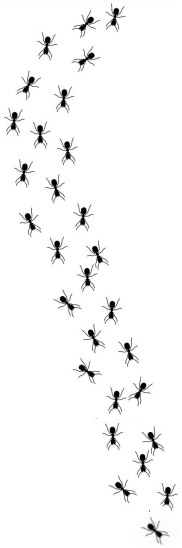
```
while (ovenBusyLightOn);
ovenBusyLightOn=true;          //Cooks now wait for a signal.
bakeCake();
ovenBusyLightOn=false;
```

In Java…

```
public class BusyThread extends java.lang.Thread {
        private int i;
        public static boolean ovenBusyLightOn=false;
        BusyThread(int i) { this.i = i; }

        public void run() {
                while (ovenBusyLightOn);
                ovenBusyLightOn=true;
                bakeCake();
                ovenBusyLightOn=false;
        }

        public void bakeCake() {
                System.out.println("Baker " + i+ " is baking!");
                System.out.println("Baker " + i+ " finished baking!");
        }

        public static void main(String[] args) {
                for(int i=1; i <= 4; ++i) {
                BusyThread c = new BusyThread(i);
                c.start();
                }
        }
}
```

```
Baker 1 is baking!
Baker 1 finished baking!
Baker 2 is baking!
Baker 2 finished baking!
Baker 3 is baking!
Baker 3 finished baking!
Baker 4 is baking!
Baker 4 finished baking!
```

Restaurant analogy contd.



Timing (*concurrency*) issues

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```
while (ovenBusyLightOn);
ovenBusyLightOn=true;          //Cooks now wait for a signal.
bakeCake();
ovenBusyLightOn=false;
```

BUT the validity of this code depends on the implementation of the ***ovenBusyLightOn*** *Boolean …*

validity depends on the implementation of the ***ovenBusyLightOn*** *Boolean …*

In Java…

```
public class BusyThread extends java.lang.Thread {
        private int i;
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        BusyThread(int i) { this.i = i; }

        public void run() {
                while (ovenBusyLightOn);
                ovenBusyLightOn=true;
                bakeCake();
                ovenBusyLightOn=false;
        }

        public void bakeCake() {
                System.out.println("Baker " + i+ " is baking!");
                System.out.println("Baker " + i+ " finished baking!");
        }

        public static void main(String[] args) {
                for(int i=1; i <= 10; ++i) {
                BusyThread c = new BusyThread(i);
                c.start();
                }
        }
}
```

```
Baker 1 is baking!
Baker 1 finished baking!
Baker 5 is baking!
Baker 5 finished baking!
Baker 2 is baking!
Baker 2 finished baking!
Baker 4 is baking!
Baker 3 is baking!
Baker 3 finished baking!
Baker 4 finished baking!
Baker 9 is baking!
Baker 9 finished baking!
Baker 8 is baking!
Baker 8 finished baking!
Baker 6 is baking!
Baker 10 is baking!
Baker 6 finished baking!
Baker 10 finished baking!
Baker 7 is baking!
Baker 7 finished baking!
```

More about this in Part II…

Concurrency problems: Race Conditions

A **race condition** is **an error** in a program where the output and/or result of the process is **unexpectedly** and **critically** dependent on the relative sequence or timing of other events.

The idea is that the events **race** each other to influence the output first.

Unintended race conditions *are incredibly common in concurrent programs.*

Nondeterminism

In sequential programs, instructions are executed **in a fixed order** determined by the program and its input. The execution of one procedure does not overlap in time with another. **Deterministic**

In concurrent programs, computational activities may overlap in time and the subprogram executions describing these activities proceed concurrently. **Nondeterministic**

it is not possible to tell, by looking at the program, what will happen when it executes.

Simple example of non-determinism: An Audition

Bob's lines are:

"Hi Alice!"

"Bye Alice!"

Alice's lines are:

"Hi Bob!"

"Bye Bob!"

They cannot **communicate** - they are in separate sound-proof rooms for recording purposes. Assume that you are taping the output from both rooms.

What will you tape?

Simple example of non-determinism: An Audition

Bob's lines are:

"Hi Alice!"

"Bye Alice!"

Alice's lines are:

"Hi Bob!"

"Bye Bob!"

Program to demonstrate

Note: in Java, concurrent programming is done by **threads**.

Why Alice and Bob? – see https://en.wikipedia.org/wiki/Alice_and_Bob

Seriously expensive race conditions (#1)

1985-1987

- **Therac-25**, a radiation therapy machine for cancer treatment used software safety systems that had a race condition between operator text input and software configuring the electron beam
  - caused by users hitting the up arrow too quickly, preventing the system from properly registering their edits.
- Resulted in an occasional 100X radiation dose, that lead to **several deaths**.

Nancy Leveson and Clark Turner, “The Investigation of the Therac-25 Accidents”, Computer, 26, 7 (July 1993) pp 18-41.

Seriously expensive race conditions (#2)

2003

a **race condition** in General Electric Energy's Unix-based **energy management system** aggravated the **USA Northeast Blackout -** biggest blackout in North American history

- trip alarm failed due to a **race condition** in alarm subsystem
  - three sagging power lines were tripped simultaneously, but the race condition prevented alerts from being raised to the monitoring technicians, delaying their awareness of the problem
- created **a cascade** of power failures
- 50 million people lost power for up to two days
- cost an estimated $6 billion

source: Scientific American

Seriously expensive race conditions (#3)

Mars Rover “Spirit”

- a six-wheeled driven, four-wheeled steered vehicle designed by NASA to navigate the surface of Mars in order to gather videos, images, samples and other possible data about the planet.

sol 136-139, June 02, 2004: *Spirit Recovers from a Low Probability Software Error*

- The Spirit designed to reboot its operating system whenever it ran into a problem that it could not resolve.
- The rover's computer was programmed to "write-protect" its software unless a specific command is given to lift that protection to make a change.
- Race condition: a “lift” command was given as part of one software routine — but before the change could be written to the rover's memory, a different routine put the write protection back in place.
- "It caused the system to say, 'I can't write to that area, so this is a software problem I can't do anything about, so therefore I have to reboot,’”
- But during the boot process found the problem with the file system. And so it rebooted itself again.
- a **reboot loop**

Eventually, the batteries drained, a scenario that activated a setting similar to "Safe Mode" on Windows PCs, where only essential files are loaded at startup. The technicians on earth could then fix this remotely.

https://mars.nasa.gov/mer/mission/rover-status/spirit/2004/all/

Race conditions

Apple "Root Bug" (2017)
Race condition in macOS High Sierra allowed users to enable the root user with a blank password just by trying to log in as root multiple times.

Anyone could gain **full root access** without authentication due to a flaw in how the system handled authentication and user creation concurrently.

MacOS High Sierra bug: blank password let anyone take control of a Mac

Apple provides emergency fix for flaw that allows access to secure preferences with username 'root' and subsequent bypass of lock screen

Samuel Gibbs *and* Matthew Weaver

Wed 29 Nov 2017 10.28 GMT

Share

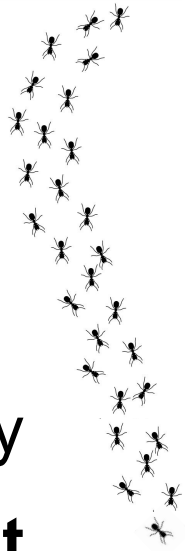
Taking Mac control ... the security flaw was initially discovered a couple of weeks ago and disclosed in an Apple developer support forum. Photograph: Apple

A serious security flaw was found in the latest version of Apple's macOS High Sierra that could allow anyone to access locked settings on a Mac using the user name "root" and no password, and subsequently unlock the computer.

Checkpoint: Race conditions

- Give an example of a race condition in everyday life.

Parallel/Concurrent complexity



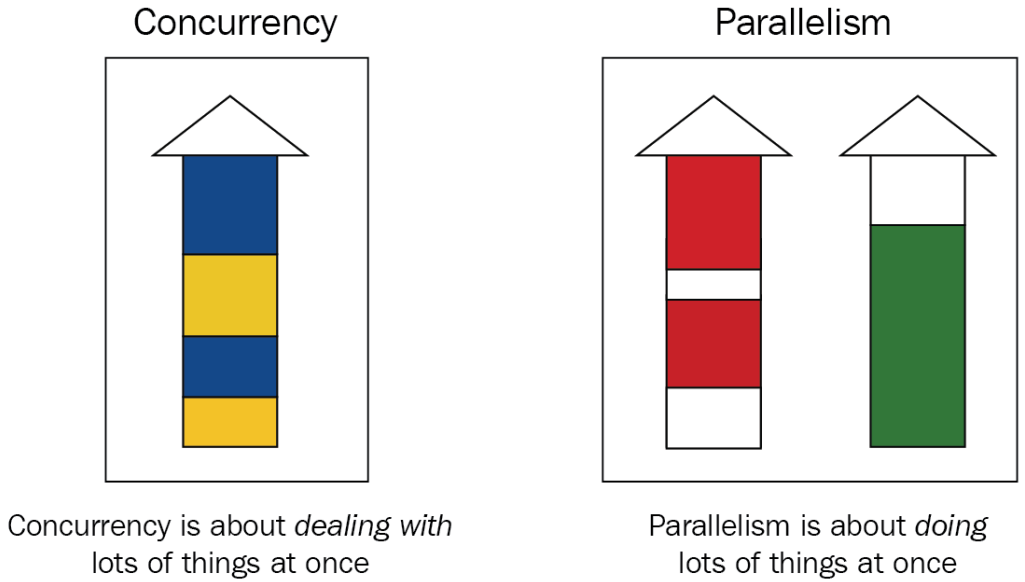
Managing parallel complexity

and the **principles and techniques** necessary

for the construction of **well-behaved** and **efficient**

parallel and *concurrent* programs

is the main subject matter of this module



This slide adapted from: Sophomoric Parallelism and Concurrency, Lecture 1, Dan Grossman, with additional image from https://www.packtpub.com/en-us/learning/how-to-tutorials/concurrency-and-parallelism-in-golang-tutorial

Difficult task

Parallel/concurrent programming is a **lot of work**…

Writing **correct** and **efficient** multithreaded programs is often **much more difficult**

than single-threaded (sequential) code

- Increased **complexity (pain)** of writing programs, especially in common languages like Java and C

So a general rule is to **stay sequential** if possible.

When is parallel/concurrent programming necessary?

When is concurrent programming necessary?

Complex programs like

- **operating systems,**
- **web browsers,**
- **Real-time** systems,
- **event-based** implementations of graphical user interfaces,
- multiuser **games**, **chats** and **ecommerce**.

handle **multiple things** happening **at once** and therefore are **multithreaded.**

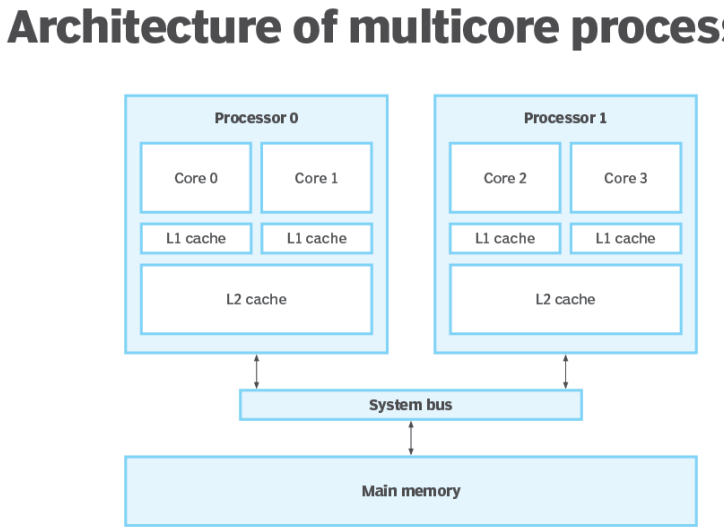
- Many concurrent threads run simultaneously.

Using multiple cores

Parallel/concurrent programming **is essential** to use the computing power of **multicore architectures**

And modern desktop and laptop computers all have **multiple cores**.

Couldn't keep making "wires exponentially smaller" so put **multiple processors** on the same chip (multicore)



The death of Moore's Law

Between 1980-2005 Moore's Law* held:

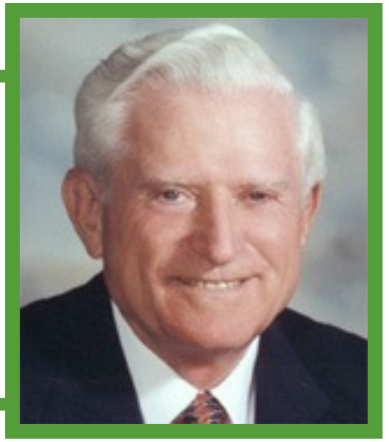
- clock speeds or desktop computers doubled every 18–24 months ("wires exponentially smaller")
- exponentially faster at running sequential programs

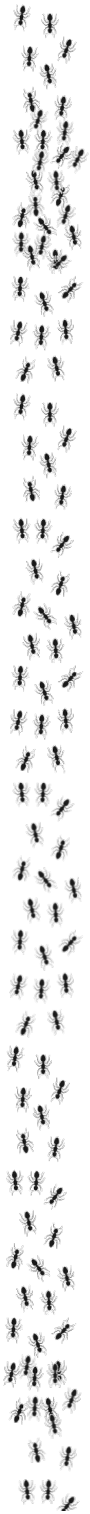
But eventually reached the **power wall**

- Increasing clock rate generates **too much heat**: power and cooling constraints limit increases in microprocessor clock speeds
- Relative cost of memory access is too high

*Not a physical Law, merely an observation.

Statement made by Gordon Moore (1929–), Cofounder of Intel, in 1965





Note: You don't need multiple cores/CPUs to have race conditions!

Concurrent execution versus time-slicing

If the computer has multiple processors then instructions from a number of processes/threads, equal to the number of physical processors, can be executed **at the same time**.

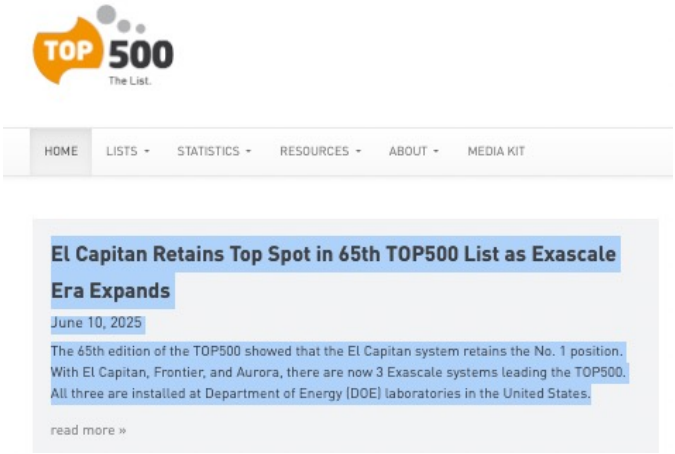
- sometimes referred to as **parallel** or ***real concurrent*** *execution.*

However it is usual to have **more active processes** than **processors**.

- the available processes are switched between processors – **timeslicing**.

NB **Processor *scheduling*** is managed by the **operating system** and the programmer has (almost) no control over it.

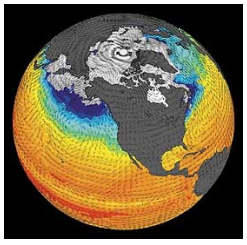
High Performance Computing



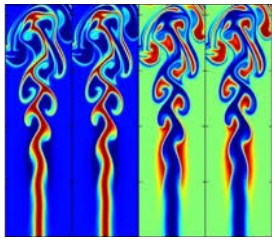
HPC uses **cutting-edge parallel computers** to solve "grand-challenge" problems.

Programmers write programs to solve such **computationally large** problems that it would take years, or centuries, for one computer to finish it.

Proteins and diseases



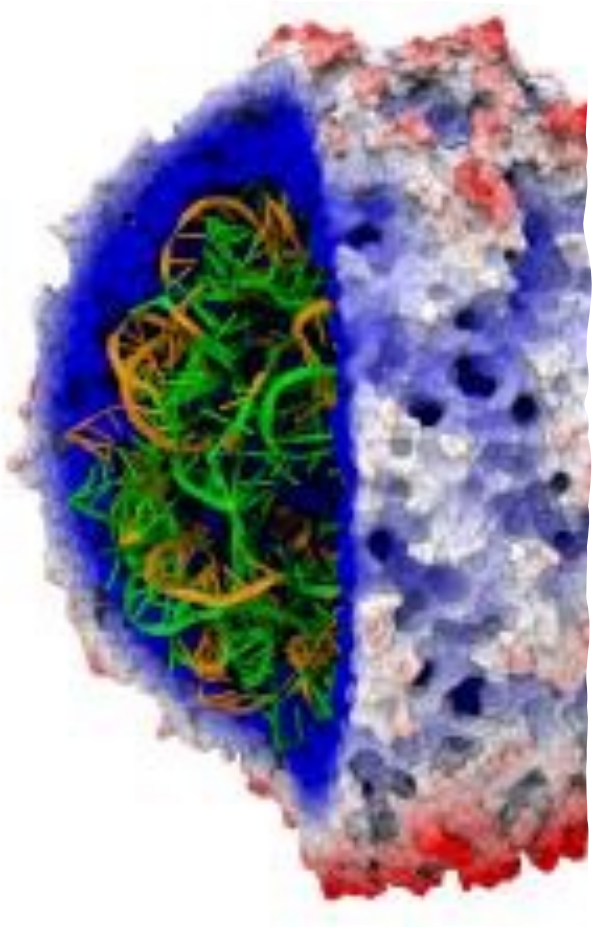
Climate change



Energy-efficient jet engines

Understanding the universe

HPC in molecular modelling



Molecular modelling simulates the behaviour and interactions of molecules to try to understand their properties.

Widely used in **drug development.**

Models can be highly accurate and computationally expensive (quantum mechanics) or less accurate and cheaper (molecular dynamics, coarse-grained models).

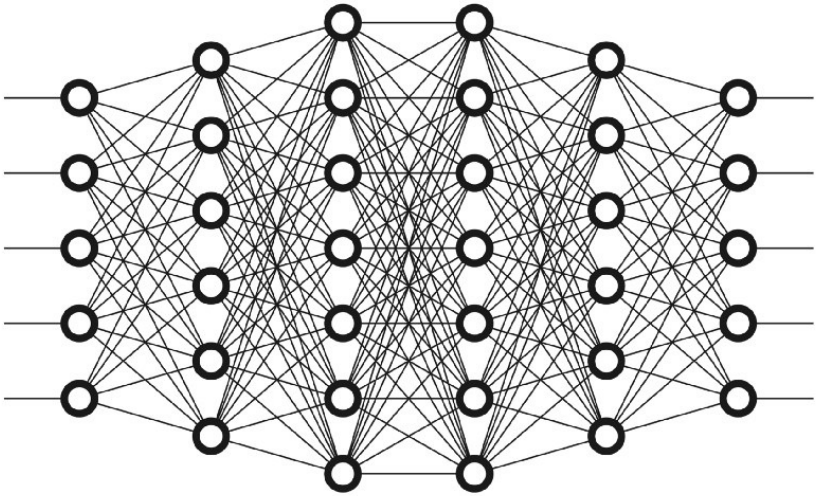
Increases in HPC power has allowed simulations to move from isolated molecules in solvent to complex aggregates –

some recent simulations have exceeded **10,000,000 atoms**.

HPC and deep learning

The recent development of deep learning has revolutionized artificial intelligence, especially for tasks such as speech and image recognition.

Neural networks date back to the 1960's, but HPC has made them widely useful



- The wide availability and low cost of GPUs and accelerated computing parallel programming tools catalysed the modern revolution in AI/deep learning.
- Simple neural networks that were once impossible to train can now be trained in hours or minutes.
- HPC is needed to train large models in a reasonable time.

HPC for animation and visual effects

- Animation studios need HPC systems.
- Computer graphics must be **rendered** into high-resolution images.
- Rendering turns a virtual 3D scene into a 2D image, requires a LOT of computing power.