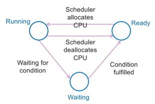
Parallel Programming | ParProg

Zusammenfassung

1. MULTI-THREADING

Parallelism *(Subprograms run simultaneously for faster programs)* vs. ***Concurrency*** *(interleaved execution of programs for simpler programs)*



Process: ***Program under Execution***, own address space *(heavy-weight. Pros: Process isolation and responsiveness, Cons: Interprocess communication overhead, expensive in creation, slow context switching and process termination)*.

Thread: ***Parallel sequence*** within a process. Sharing the same address space, but separate stack and registers *(lightweight because most of the overhead already happened in the process creation)*.

Multi-threads: Changes made by one thread to shared resources will be ***seen*** by other threads.

Context switch: Required when changing threads. ***Synchronous*** *(Thread waiting for condition)* or ***Asynchronous*** *(Thread gets released after defined time)*

Multitasking: ***Cooperative*** *(Threads must explicitly initiate context switches, scheduler can't interrupt)* or ***preemptive*** *(scheduler can asynchronously interrupt thread via timer interrupt)*

JVM Thread Model: JVM is a ***process in the OS***. It runs as long as threads are running *(Exception: threads marked as daemon with `setDaemon(true)` will not be waited upon)*. Threads are realized by the ***thread class*** and the ***interface Runnable***. Code to be run in a Thread is within a overridden `run()`

1.1. STARTING A THREAD

As a anonymous function (Lambda): `var myThread = new Thread(() → { /* thread behaviour */ }); myThread.start();`

As a named function: `var myThread = new Thread(() → AssyFunct()); myThread.start();`

With explicit runnable implementation:

```
class MyThread implements Runnable {
  @Override
  public void run() { /* thread behavior */ }}
  var myThread = new Thread(new MyThread());
  myThread.start();}
```

In C#: `var myThread = new Thread(() ⇒ { ... }); myThread.Start(); ... myThread.Join();`

Multi-Thread Example (no synchronization)

```
public class MultiThreadTest {
  public static void main(String[] args) {
    var a = new Thread(() → multiPrint("A"));
    var b = new Thread(() → multiPrint("B"));
    a.start(); b.start(); System.out.println("main finished");
  }
  static void multiPrint(String label) {
    for (int i = 0; i < 10; i++) { System.out.println(label + ": " + i);
}}}
```

The printout of this function varies. It can be all possible combinations of A's and B's due to the non-deterministic scheduler

Thread Join: Waiting for a thread to finish *(`t2.join()` blocks as long as t2 is running)*.

```
var a = new Thread(() → multiPrint("A")); var b = new Thread(() → multiPrint("B"));
System.out.println("Threads start"); a.start(); b.start(); // ...
a.join(); b.join(); System.out.println("Threads joined");
```

Thread States: ***`Blocked`*** *(Thread is blocked and waiting for a monitor lock)*, ***`New`*** *(Thread has not yet started)*, ***`Runnable`*** *(Thread is runnable (Ready to run or running))*, ***`Terminated`*** *(Thread is terminated)*, ***`Timed_Waiting`*** *(Thread is waiting with a specified waiting time `Thread.sleep(ms)`/`Thread.join(ms)`)*, ***`Waiting`*** *(Thread is waiting)*

Yield: Thread is done processing for the moment and hints to the scheduler to release the processor. The scheduler can ignore this. Thread enters into ready-state. *(`Thread.yield()`)*

Interrupts: Threads can also be interrupted from the outside *(`myThread.interrupt()`, Thread can decide what to do upon receiving an interrupt)*. If the thread is in the `sleep()`, `wait()` or `join()` methods, a `InterruptException` is thrown. Otherwise a flag is set that can be checked with `interrupted()`/`isInterrupted()`

Exceptions: Exceptions thrown in `run()` can't be propagated to the Main thread. The exception needs to be handled within the code executed on the thread.

Thread Methods: ***`currentThread():`*** *(Reference to current thread)*, ***`setDaemon(true):`*** *(Mark as daemon)*, ***`getId()/getName():`*** *(Get thread ID/Name)*, ***`isAlive():`*** *(Tests if thread is alive)*, ***`getState():`*** *(Get thread state)*

2. MONITOR SYNCHRONIZATION

Threads run arbitrarily. ***Restriction of concurrency*** for deterministic behavior.

Communication between threads: Sharing access to fields and the objects they refer to. Efficient, but poses problems: ***Thread interference*** and ***memory consistency errors***.

Critical Section: Part of the code which must be executed by only 1 thread at a time for the values to stay consistent. Implementation with ***mutual exclusion***.

```
class BankAccount {
  private int balance = 0;
  public void deposit(int amount){
    // enter critical section
    synchronized(this) {
      this.balance += amount;
    } // exit critical section
  }
}
```

`synchronized`: Body of method with the `synchronized` keyword is a critical section. Guarantees ***memory consistency*** and a ***happens-before relationship***. Impossible for two invocations of a synchronized method on the same object to interleave. Other threads are ***blocked*** until the current thread is done with the object. Every object has a ***Lock*** *(Monitor-Lock)*. Maximum 1 thread can acquire the lock. Entry of a `synchronized` method acquires the lock of the object, the exit releases it.
`public synchronized void deposit(int amount) { this.balance += amount; }`
Can also be used within a method, the ***object that should be locked*** must be specified.
`synchronized(this) { this.balance += amount; }`

Exit synchronized block: End of the block, `return`, unhandled exceptions

2.0.1. Monitor Lock

A monitor is used for ***internal mutual exclusion***. Only one thread operates at a time in Monitor. All non-private methods are synchronized. Threads can ***wait in Monitor*** for condition to be fulfilled. Can be ***inefficient*** with different waiting conditions, has ***fairness-problems*** and ***no shared locks***.

Recursive Lock: A thread can acquire the same lock through recursive calls. Lock will be free by the last release.

Busy Wait: Running `yield` or `sleep` in a loop doesn't release the lock and is inefficient. Use `wait`.

`wait()`: Waits on a condition. Temporarily releases Monitor-Lock so that other threads can run. Needs to be ***wrapped into a `while` loop*** to check if the wake up condition has been met.

Wakeup signal: Signalling a condition/thread in Monitor. ***`notify()`*** signals any waiting thread *(sufficient if all threads wait for the same thing, so it does not matter which one comes next - uniform waiters or if only one single thread can continue like in a turnstile)*, ***`notifyAll()`*** wakes up all threads *(i.e. one deposit can satisfy multiple withdraws, does not guarantee fairness)*. If a thread is woken up, it goes from the ***inner waiting room*** *(waiting on a condition)* into the ***outer waiting room*** *(Thread has not started yet)* where it waits for entry to the Monitor. There is no shortcut.

`IllegalMonitorStateException` is thrown if `notify`, `notifyAll` or `wait` is used outside synchronized.

```
// Java
class BankAccount {
  private int balance = 0;
  // Entry in the monitor
  public synchronized void withdraw
  (int amount)
  throws InterruptedException {
    while (amount > balance) { // not if
      wait(); // wait on a condition
    }
    balance -= amount;
  } // release / leave monitor
  public synchronized void deposit
  (int amount) {
    balance += amount;
    notifyAll(); // Wakes up all waiting
threads in monitor inner waiting area
}}
```

```
// C# .NET
class BankAccount {
  private decimal balance;
  private object syncObject = new();
  public void Withdraw(decimal amount) {
    lock (syncObject) {
      while (amount > balance) {
        Monitor.Wait(syncObject);
      }
      balance -= amount;
  }}
  public void Deposit(decimal amount) {
    lock(syncObject) {
      balance += amount;
      Monitor.PulseAll(syncObject);
}}}
```

3. SPECIFIC SYNCHRONIZATION PRIMITIVES

3.1. SEMAPHORE

Allocation of a limited number of free resources. Is in essence a ***counter***. If a resource is ***acquired***, `count--`, if a resource is ***released***, `count++`. Can wait until resource becomes available. Can also acquire/release multiple permits at once atomically.

```
public class Semaphore {
  private int value; public Semaphore(int initial) { value = initial; }
  public synchronized void acquire() throws InterruptedException {
    while (value ⩽ 0) { wait(); } value--; }
  public synchronized void release() { value++; notify(); } }
```

General Semaphore: `new Semaphore(N)` *(Counts from 0 to N for limited permits to access a resource)*

Binary Semaphore: `new Semaphore(1)` *(Counter 0 or 1 for mutual exclusion, open/locked)*

Fair Semaphore: `new Semaphore(N, true)` *(Uses FIFO Queue aging for fairness. Slower than non-fair variant.)*

Semaphores are ***powerful***, any synchronization can be implemented. But relatively ***low-level***.

```
class BoundedBuffer<T> {
  private Queue<T> queue = new LinkedList<>();
  private Semaphore upperLimit = new Semaphore(Capacity, true); //how many free?
  private Semaphore lowerLimit = new Semaphore(0, true); // how many full?
  public void put(T item) throws InterruptedException {
    upperLimit.acquire(); // No. of free places - 1
    synchronized (queue) { queue.add(item);}
    lowerLimit.release(); } // No. of full places + 1
  public T get() throws InterruptedException {
    T item;
    lowerLimit.acquire(); // No. of full places - 1
    synchronized (queue) { item = queue.remove(); }
    upperLimit.release(); // No. of free places + 1
    return item; }}
```

3.2. LOCK & CONDITION

Monitor with ***multiple waiting lists*** and conditions. Independent from Monitor locks.

Lock-Object: Lock for entry in the monitor *(outer waiting room)*

Condition-Object: Wait & Signal for a specific condition *(inner waiting room)*.

ReentrantLock: Class in Java, ***alternative to `synchronized`***. Allows multiple locking operations by the same thread and supports nested locking *(Thread is able to re-enter the same lock)*.

Condition: Factors out the Object monitor methods *(`wait`, `notify` and `notifyAll`)* into distinct objects to give the effect of having multiple wait-sets per object, by combining them with the use of arbitrary Lock implementations. A ***Condition replaces the use of the Object monitor methods***.

`condition.await()`: Throws an InterruptedException if the current thread has its interrupted status set on entry to this method or is interrupted while waiting *(`finally` frees the lock in case of interrupt)*.

Buffer with Lock & Condition

```
class BoundedBuffer<T> {
  private Queue<T> queue = new LinkedList<>();
  private Lock monitor = new ReentrantLock(true); // fair queue
  private Condition nonFull = monitor.newCondition();
  private Condition nonEmpty = monitor.newCondition();
  ...
  public void put(T item) throws InterruptedException {
    monitor.lock(); // Lock queue
    try { while (queue.size() == Capacity) { nonFull.await(); }
      queue.add(item); nonEmpty.signal(); } finally { monitor.unlock(); }
  } // signalAll() if uniform waiters
  public T get() throws InterruptedException {
    monitor.lock(); // wait for queue to be filled & signal to other queue
    try { while (queue.size() == 0) { nonEmpty.await(); }
      T item = queue.remove(); nonFull.signal(); return item;
    } finally { monitor.unlock(); } // always release lock, even after Execption
}}
```

3.3. READ-WRITE LOCK

Mutual exclusion is ***unnecessary for read-only*** threads. So one should allow parallel reading access, but implement mutual exclusion for write access.

Parallel	*Read*	*Write*
Read	Yes	No
Write	No	No

```
ReadWriteLock rwLock = new ReentrantReadWriteLock(true); // true for fairness
rwLock.readLock().lock(); // shared Lock
// read-only accesses
rwLock.readLock().unlock();
rwLock.writeLock().lock(); // exclusive Lock
// write (and read) accesses
rwLock.writeLock().unlock();
```

3.4. COUNT DOWN LATCH

Synchronization with a counter that can only ***count down***. Threads can wait until counter ≤ 0, or they can count down. The Latches can only be used once.

```
var ready = new CountDownLatch(N); var start = new CountDownLatch(1);
```

```
ready.countDown(); // wait for N cars
start.await(); // await race start
```

```
ready.await(); // wait for all cars ready
start.countDown(); // start the race
```

3.5. CYCLIC BARRIER

Meeting point for fixed number of threads. Threads wait ***until everyone arrives***. Is ***reusable***, threads can synchronize in multiple rounds at the same barrier *(Simplifies example above)*.

```
var start = new CyclicBarrier(N); start.await(); // all cars race as they're here
```

3.6. EXCHANGER

Rendez-Vous: Barrier with ***information exchange*** for 2 parties. Without exchange: `new CyclicBarrier(2)`, with exchange: `Exchanger.exchange(something)`. The Exchanger blocks until another thread also calls `exchange()`, returns argument x of the other thread.

```
var exchanger = new Exchanger<Integer>();
for (int count = 0; count < 2; count++) { // odd n.of exch.: last one blocks
  new Thread(() → {
    for (int in = 0; in < 5; in++) {
      try {
        int out = exchanger.exchange(in);
        System.out.println(Thread.currentThread().getName() + " got " + out);
      } catch (InterruptedException e) { }
    } }).start(); }
```

4. CONCURRENCY HAZARDS

4.1. RACE CONDITIONS

Insufficiently synchronized access to shared resources. The ***order of events*** affects the ***correctness*** of the program. Leads to ***non-deterministic behavior***. Can occur without data race, but data race is often the cause.

Race Condition without data race: The critical section is not protected. Data Race is eliminated using synchronization, but there is no synchronization over larger blocks, so race conditions are still possible *(i.e. non-atomic incrementing)*.

4.2. DATA RACE

Two threads in a single process ***access the same variable*** concurrently without synchronization, at least one of them is a ***write access***.

Synchronize Everything? May not help and is expensive. So no.

4.3. THREAD SAFETY

Dispensable cases in synchronization: ***Immutable Classes*** *(Declaring all fields private and final and don't provide setters)*, ***Read-only Objects*** *(Read-only accesses are thread-safe)*

Confinement: Object belongs to only one thread at a time. ***Thread Confinement*** *(Object belongs to only one thread)*, ***Object Confinement*** *(Object is encapsulated in other synchronized objects)*

Thread safe: A data type or method that behaves correctly when used from multiple threads as if it was running in a single thread without any additional coordination *(Java concurrent collections)*.

Thread Safety: Avoidance of Data Races. When no sharing is intended, give each thread a private copy of the data. When sharing is important, provide explicit synchronization.

4.4. DEADLOCKS

Happens when threads lock each other out, prohibiting both from running. Programs with potential deadlock are not considered correct. Threads can suddenly block each other.

```
// Thread 1
synchronized(listA) {
  synchronized(listB) {
    listB.addAll(listA);
}}
```

```
// Thread 2
synchronized(listB) {
  synchronized(listA) {
    listA.addALl(listB);
}}
```

Both threads in this scenario have ***locked each other out***, the program cannot continue.

Livelock: Threads have blocked each other permanently, but still execute wait instructions and therefore consume CPU during deadlock.

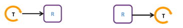
```
// Thread 1
b = false; while(!a) { } ... b = true;
```

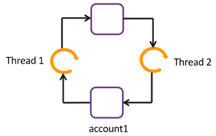
```
// Thread 2
a = false; while(!b) { } ... a = true;
```

4.4.1. Resource Graph

Thread T ***waits for Lock*** of Resource R

Thread T ***acquires Lock*** of Resource R





Deadlocks can be identified by ***cycles in the resource graph***.

Deadlock Avoidance: Introduce ***linear blocking order***, lock nested only in ascending order. Or use ***coarse granular locks***
(When ordering does not make sense, e.g. block the whole Bank to block all accounts)

4.5. STARVATION

A thread never gets chance to access a resource. ***Avoidance:*** Use fair synchronization constructs. *(Aging, Enable fairness in previous synchronization constructs. Monitor and Thread priorities have a fairness problem.)*

4.6. PARALLELISM CORRECTNESS CRITERIA

Safety: No race conditions and no deadlocks, ***Liveness:*** No starvation

4.7. .NET SYNCHRONIZATION PRIMITIVES

Monitor with sync object: `private object sync = new(); lock(sync){ ... }`. Uses `Monitor.Wait(sync)`, `Monitor.PulseAll(sync)`. Uses fair FIFO-Queue. ***Lacks:*** No fairness flag, no Lock & Condition. ***Additional:*** `ReadWriteLockSlim` for Upgradeable Read/Write, Semaphores can also be used at OS level, Mutex. Collections are ***not*** Thread-safe.

5. THREAD POOLS

Threads do have a ***cost***. Many threads ***slow down*** the system. There is also a ***Memory Cost***, because there is a stack for each thread. ***Recycle*** threads for multiple tasks to avoid this.

Tasks: Define ***potentially parallel*** work packages. Passive objects describing the functionality.

Thread Pool: Task are queued. A much smaller number of ***working threads*** grab tasks from the queue and execute them. A task must run to completion before a thread can grab a new one.

Scalable Performance: Programs with tasks run ***faster on parallel machines***. This allows the exploitation of parallelism ***without thread costs***. The number of threads can be ***adapted*** to the system. *(Rule of thumb: # of Worker Threads = # processors + 1 (Pending I/O Calls))*

Any task must ***complete execution*** before its worker thread is free to grab another task. Exception: nested tasks.

Advantages: ***Limited number of threads*** *(Too many threads slow down the system or exceed available memory)*, ***Thread recycling*** *(save thread creation and release)*, ***Higher level of abstraction*** *(Disconnect task description from execution)*, ***Number of threads configurable*** on a per-system basis.

Limitations: Task must not wait for each other *(except sub-tasks)*, results in deadlocks *(if one task T_1 is waiting for something the task T_2 behind him in the Queue should provide, but T_2 waits for T_1 to finish, a deadlock occurs)*

5.1. JAVA THREAD POOL

```
// Task Launch
var threadPool = new ForkJoinPool();
Future<Integer> future = threadPool.submit(() → { // submit task into pool
  int value = ...; /* long calculation */ return value;
});
```

5.1.1. Future<T>

Represents a ***future result*** that is to be computed *(asynchronous)*. Acts as proxy for the result that may be not available yet because the task has not finished. Usage via ***`.submit()`*** *(submits task into pool and launches task)*, ***`.get()`*** *(waits if necessary for computation to complete and then retrieves its result)* and ***`.cancel()`*** *(Attempts to cancel execution of this task, removes it from queue)*. Task ends when a unhandled exception occurs. It is included in the `ExecutionException` thrown by `get()`.

5.1.2. Fire and Forget

Task are started ***without retrieving results*** later *(`submit()` without `get()`)*. Task is run, but Exceptions do not get catched.

5.1.3. Count Prime Numbers

```
// Sequential
int counter = 0; for (int n = 2; n < N; n++) { if (isPrime(n)) { counter++}};
// Parallel and Recursive
class CountTask extends RecursiveTask<Integer> { //RecursiveAction: no return value
  private final int lower, upper;
  public CountTask(int lower, int upper) { this.lower = lower; this.upper = upper;}
  protected Integer compute() {
    if (lower == upper) { return 0; }
    if (lower + 1 == upper) { return isPrime(lower) ? 1 : 0;}
    int middle = (lower + upper) / 2;
    var left = new CountTask(lower, middle);
    var right = new CountTask(middle, upper);
    left.fork(); right.fork();
    return right.join() + left.join();
}}
int result = new CountTaks(2,N).invoke(); // invokeAll() to start multiple tasks
```

5.1.4. Pairwise sum (recursive)

```
class PairwiseSum extends RecursiveAction {
  private final int[] array;
  private final int lower, upper;
  private static final int THRESHOLD = 1; // configurable
  public PairwiseSum(int[] array, int lower, int upper) {
    this.array = array; this.lower = lower; this.upper = upper;
  }
  protected void compute() {
    if (upper - lower > THRESHOLD) {
      int middle = (lower + upper) / 2;
      invokeAll(
        new PairwiseSum(array, lower, middle),
        new PairwiseSum(array, middle, upper));
    } else {
      for (int i = lower; i < upper; i++) {
        array[2*i] += array[2*i+1]; array[2*i+1] = 0;
}}}}
```

5.1.5. Work Stealing Thread Pool

Jobs get submitted into the ***global queue***, which distributes the jobs to the ***local queues*** of each worker thread. If one thread has no work left, it can ***"steal" work from another threads*** local queue instead of the global queue. This ***distributes*** the scheduling work over idle processors.

5.2. JAVA FORK JOIN POOL

Special Features: Fire-and-forget tasks may not finish, worker threads run as daemon threads. Automatic degree of parallelism *(Default: As much worker threads as Processors)*.

5.3. .NET TASK PARALLEL LIBRARY (TPL)

Preferred way to write multi-threaded and parallel code. Provides public types and APIs in `System.Threading` and `System.Threading.Tasks` namespaces. ***Efficient default thread pool*** *(tasks are queued to the ThreadPool, supports algorithms to provide load balancing, tasks are lightweight)*, has ***multiple abstraction layers*** *(Task Parallelization: use tasks explicitly, Data Parallelization: use parallel statements and queries using tasks implicitly)*, Asynchronous Programming and PLINQ.

```
// Task with return value in C#
Task<int> task = Task.Run(() ⇒ {
  int total = ... // some calculation
  return total;
});
Console.Write(task.Result); //Blocks until task is done and returns the result
```

```
// Nested Tasks
var task = Task.Run(() ⇒ {
  var left = Task.Run(() ⇒ Count(leftPart));
  var right = Task.Run(() ⇒ Count(rightPart));
  return left.Result + right.Result;
});
static Task<int> Count(...part) {...}
```

5.3.1. Parallel Statements in C#

Execute ***independent*** statements ***potentially in parallel*** *(Start all tasks, implicit barrier at the end)*.

```
Parallel.Invoke(
  () ⇒ MergeSort(l,m),
  () ⇒ MergeSort(m,r)
);
```

Execute ***loop-bodies potentially in parallel*** *(Queue a task for each item, implicit barrier at the end)*.

```
Parallel.ForEach(list,
  file ⇒ Convert(file));
Parallel.For(0, array.Length,
  i ⇒ DoComputation(array[i]));
```

Parallel Loop Partitioning: Loop with lots of quickly executing bodies. It would be ***inefficient*** to execute each iteration in parallel. Instead, TPL ***automatically groups multiple bodies*** into a single task. There are ***4 kinds of partitioning schemes:*** Range *(equally sized)*, Chunk *(partitions start small and grow bigger)*, Stripe *(n-sized partitions, where n "small number, sometimes 1")* and Hash partitioning *(default: if input is indexable then range partitioning, else chunk partitioning)*.

5.3.2. PLINQ

LINQ: Set of technologies based on the integration of SQL-like query capabilities directly into C#.

PLINQ: Is a parallel implementation of LINQ. Benefits from ***simplicity*** and ***readability*** of LINQ with the power of parallel programming by creating segments from its data. Analog to Java Stream API.

```
from book in bookCollection.AsParallel() where book.Title.Contains("Concurrency")
select book.ISBN // Random Order
```

```
from number in inputList.AsParallel().AsOrdered() select IsPrime(number)
// Maintains order but is slower
```

5.3.3. Thread Injection

TPL adds new worker threads ***at runtime*** every time a work item completes or every 500ms.

Hill Climbing Algorithm: ***Maximize throughput*** while using as ***few threads*** as possible. Measures throughput & ***varies*** number of worker threads. ***Avoids deadlock*** with task-dependencies *(but inefficiently since not designed for this. Deadlocks with `ThreadPool.SetMaxThreads()` are still possible)*. We should keep ***parallel tasks short*** to better profit from this automatic performance improvement.

6. ASYNCHRONOUS PROGRAMMING

Unnecessary Synchrony: Blocking method calls are often used without need *(Long running calculations, I/O calls, database or file accesses)*. With an ***asynchronous call***, other work can continue while waiting on the result of the long operation.
`var task = Task.Run(LongOperation); /* other work */ int result = task.Result;`

Kinds of Asynchronisms: ***Caller-centric*** *("pull", caller waits for the task end and gets the result, blocking call)*, ***Callee-Centric*** *("push", Task hands over the result directly to successor / follower task)*

Task Continuations: Define task whose start is linked to the end of the predecessor task.

```
// C# .NET
Task
  .Run(task1)
  .ContinueWith(task2)
  .ContinueWith(task3);
```

```
// Java (there can be multiple Apply/AcceptAsync calls)
CompletableFuture
  .supplyAsync(() → longOP) // runAsync for return void
  .thenApplyAsync(v → 2*v) // returns value
  .thenAcceptAsync(v → ... .println(v)); // returns void
```

Multi-Continuation: Continue when ***all*** tasks are finished:
`Task.WhenAll(task1, task2).ContinueWith(continuation);`
Continue when ***any*** of the tasks are finished *(other threads get lost after first thread is done)*:
`Task.WhenAny(task1, task2).ContinueWith(continuation);`
(Exceptions in fire & forget task get ignored, i.e. `Task.Run(() ⇒ { ...; throw e; })`)

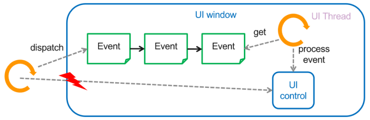
Exception Handling: Synchronously ***`Wait()`*** for the ***whole task-chain*** at the end. ***Register for unobserved exceptions*** with ***`TaskScheduler.UnobservedTaskException`*** *(Receives unhandled exceptions from fire & forget tasks)*. This should be executed as soon as the task object is dead *(Garbage Collector)*.

Java `CompletableFuture`: ***Modern asynchronous*** programming in Java. Also has ***Multi-Continuation*** with `CompletableFuture.allOf(future1, future2)` and `CompletableFuture.any(...)`

6.1. NON-BLOCKING GUI'S

Use case: If a UI is doing a long task, it should not freeze.

GUI Thread Model: Only ***single-threading*** *(Only a special UI-thread is allowed to access UI-components)*. The ***UI thread*** loops to process the ***event queue***.



GUI Premise: ***No long operations*** in UI events, or else blocks UI. ***No access to UI-elements by other threads***, or else incorrect *(Exception in .NET & Android, Race Condition in Javas Swing)*.

6.1.1. Non-Blocking UI Implementation

```
// C# .NET
void buttonClick(...) {
  var url = textBox.Text;
  Task.Run(() ⇒ {
    var text = Download(url);
    Dispatcher.InvokeAsync(() ⇒ {
      label.Content = text;
    });
  });
}
```

```
// Java
button.addActionListener(event →
  var url = textField.getText();
  CompletableFuture.runAsync(() → {
    var text = download(url); // to worker thread
    SwingUtilities.invokeLater(() → {
      textArea.setText(text); // to UI thread
    });
  });
)
```

Java `invokeLater`: To be executed ***asynchronously*** on the event dispatching thread. Should be used when an ***application thread*** needs to ***update the GUI***.

6.2. C# ASYNC/AWAIT

More ***readable*** than the "spaghetti code" in the chapter before. This is the same code as before.

```
...
var url = textBox.Text;
var text = await DownloadAsync(url);
label.Context = text;
...
```

```
async Task<string> DownloadAsync(string url) {
  var web = new HttpClient();
  string result = await web.GetStringAsync(url);
  return result;
}
```

`async` for methods: Caller may not be blocked during the entire execution of the async method.
`await` for tasks: "Non-blocking wait" on task-end / result.

Execution Model: Async methods run partly ***synchronous*** *(as long as there is no blocking await)*, partly ***asynchronous*** *(until the awaited task is complete)*.

Mechanism: Compiler dissects method into ***segments*** which are then executed completely synchronously or asynchronously.

Different Execution Scenarios: ***Case 1:*** Caller is a "normal" thread *(Usual case, Continuation is executed by a TPL-Worker-Thread)*, ***Case 2:*** Caller is a UI-thread *(Continuation is dispatched to the UI thread and processed by the UI-Thread as event)*

Async Return Value Types: ***`void`*** *("fire-and-forget")*, ***`Task`*** *(No return value, allows waiting for end)*, ***`Task<T>`*** *(For methods having return value of type T)*.

Async without await: Execute long running operation explicitly in task with `await Task.Run()`.

```
public async Task<bool> IsPrimeAsync(long number) {
  return await Task.Run(() ⇒ {
    for (long i = 2; i*i ⩽ number; i++) {
      if (number % i == 0) { return false; }
    } return true;
  }); }
```

7. MEMORY MODELS

Lock-Free Programming: ***Correct*** concurrent interactions ***without using locks***. Use guarantees of memory models. Goal is ***efficient synchronization***.

Problems: Memory accesses are seen in ***different order*** by different threads, except when ***synchronized*** and at ***memory barriers*** *(weak consistency)*. Optimizations by compiler, runtime system and CPU. Instructions are reordered or eliminated by optimization.

Memory model: Part of language semantics, there exist different models: ***sequential consistency (SC)*** *(Order of execution cannot be changed. Too strong a consistency model)* and the ***Java Memory Model*** *(a "weak" memory model)*.

7.1. JAVA MEMORY MODEL (JMM)

Interleaving-based semantics. Minimum warranties: ***Atomicity, Visibility and Ordering***.

7.1.1. Atomicity

An ***atomic*** action is one that happens ***all at once*** *(So no thread interference)*. Java guarantees that read/writes to primitive data types up to 32 Bit, Object-References *(strings etc.)* and long and double *(with `volatile` keyword)* are atomic. ***A single read/write is atomic.*** Atomicity does ***not imply visibility***.

7.1.2. Visibility

Guaranteed visibility between threads. ***Lock Release & Acquire*** *(Memory writes before release are visible after acquire)*, ***`volatile` Variable*** *(Memory writes up to and including the write to volatile variables are visible when reading the variable)*, ***Thread/Task-Start and Join*** *(Start: input to thread; Join: thread result)*, ***Initialization of `final` variables*** *(Visible after completion of the constructor)*, ***`final` fields***.

7.1.3. Ordering

Java Happens Before: "Happens before" defines the ***ordering and visibility guarantees*** between actions in a program. It ensures that changes made by one thread become visible to others. An ***unlock*** of a monitor ***happens-before*** every subsequent lock of that same monitor.

Java Ordering Guarantees: Writes before Unlock → reads after lock, `volatile` write → `volatile` read, Partial Order. Synchronization operations are never reordered. *(Lock/Unlock, volatile-accesses, Thread-Start/Join.)*

7.2. SYNCHRONIZATION

Rendez-Vous: Primitive attempt to synchronize threads.

```
// Java
volatile boolean a = false, b = false;
// Thread 1
a = true; while( !b ) { ... }
// Thread 2
b = true; while( !a ) { ... }
```

No reordering because `a` and `b` are `volatile`.

```
// C# .NET
volatile bool a = false, b = false;
// Thread 1
a = true; Thread.MemoryBarrier();
while (!b) { ... }
// Thread 2
b = true; Thread.MemoryBarrier();
while (!a) { ... }
```

Spin-Lock with atomic Operation:

```
public class SpinLock {
  private final AtomicBoolean locked = new AtomicBoolean(false);
  public void acquire() { while( locked.getAndSet(true) ) {...} }
  public void release() { locked.set(false); }
}
```

Java Atomic Classes: Classes for boolean, Integer, Long, References and Array-Elements. Different kinds of atomic operations, ***`addAndGet()`***, ***`getAndAdd()`*** etc.

Operations on atomic data classes: `boolean getAndSet(boolean newValue)`
Atomically sets to the given value and returns the previous value.
`boolean compareAndSet(boolean expect, boolean update)`
Sets `update` only when read value is equal to `expect`. Returns true when successful.

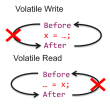
Optimistic Synchronization:

```
do { oldV = v.get(); newV = result; } while(!v.compareAndSet(oldV, newV));
```

Lambda-Variants: `AtomicInteger s = new AtomicInteger(2); s.updateAndGet(x → x * x);`

7.3. .NET MEMORY MODEL

Main differences to JMM: ***Atomicity*** *(long/double also not atomic with volatile)*, ***Ordering and Visibility*** *(only half and full fences)*. ***Atomic Instructions*** with the `Interlocked` class



7.3.1. Half Fence (Volatile)

Reordering in one direction still possible. ***Volatile Write:*** Release semantics *(Preceding memory accesses are not moved below it, but later operations can be executed before the write)*. ***Volatile Read:*** Acquire semantics *(Subsequent memory accesses are not moved above it, but previous operations can be executed after the read)*

7.3.2. Full Fence (Memory Barrier)

Disallows reordering in both directions. `Thread.MemoryBarrier();`

8. GPU (GRAPHICS PROCESSING UNIT)

End of Moores Law: We can no longer gain performance by "growing" sequential processors. Instead, we *improve performance* by running code in *parallel* on *multi-core (CPUs)* *(Low Latency)* and many-core or *massively parallel co-processors (GPUs)* *(high throughput)*.

GPU's are specialized electronic circuits designed to accelerate the computation of *computer graphics*. They are faster than CPUs for suitable algorithms on large datasets. *Useful* for calculations which consist of *multiple independent sub-calculations*, not very useful for calculations where the results rely on the previous results *(like Fibonacci)*.

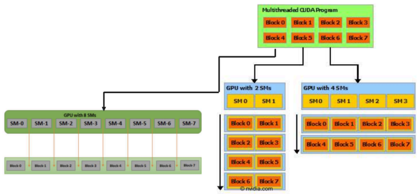
High Parallelization: A *CPU* offers few cores *(4, 8, 16, 64)* and is very fast. Programming is easier. A *GPU* offers a very large number of cores *(512, 1024, 3584, 5760)* and has very specific slower processors. It is optimized for throughput. Programming is more difficult.

GPU Structure: A GPU consists of multiple *Streaming Multiprocessors (SM)* which in turn consist of multiple *Streaming Processors (SP)* *(e.g. 1-30 SM, 8-192 SPs per SM)*.

SIMD: Single Instruction Multiple Data. The *same instruction* is executed simultaneously on *multiple cores* working on *different data elements* *(Vector parallelism)*. Saves fetch & decode instructions.

SISD: Single Instruction Single Data. Purely *sequential* calculations.

SIMT: Single Instruction Multiple Threads. The same instruction is executed in different threads over different data.



8.1. LATENCY VS. THROUGHPUT

Latency: *Elapsed time* of an event *(Walking from point A to B takes one minute, the latency is one minute)*.

Throughput: *The number of events* that can be executed per unit of time *(Bandwidth)*

There is a *tradeoff* between latency and throughput. Increasing throughput by pipelined processing, latency most often also increases. All pipeline stages must operate in *lockstep*. The *rate of processing* is determined by the *slowest step*.

Pipelining: Run processes in an overlapping manner.

Example: A program consists of two operations: Transfer data from CPU memory to GPU memory (T_1 units = *20ms*), Execute computation on the device (T_2 units = *60ms*).

What is the *latency* (non-pipelined)? $20 + 60 = \underline{80\text{ms}}$.

What is the *throughput* (pipelined)? Every *60ms* an operation is finished.

Throughput = $\frac{1}{60}$ operations/ms.

8.2. CPU VS GPU

CPUs	*GPUs*
– *Low latency* – Few but *optimized cores* – *General purpose* – Architecture and Compiler help to run any code fast	– Can execute *highly parallel data* operations – Simple but a *lot of cores* with cache per core – very useful for problems which consist of a *lot of independent data elements* – Efficiency must be achieved by *optimizing* the program
Aim: low latency per thread	**Aim:** high throughput

8.3. NUMA MODEL

NUMA stands for *Non-Uniform Memory Access*. CPUs on host and GPU devices each have local memories. There is *no common main memory* between the two, so *explicit transfer* between CPU and GPU is needed. There is also *no garbage collector* on the GPU.

8.4. CUDA

Computer Unified Device Architecture. Is a *parallel computing platform and an API* for Nvidia GPU that allows the host program to use GPUs for general purpose processing.

CUDA Execution

1. `cudaMalloc`: GPU memory allocate
2. `cudaMemcpy`: Data transfer to GPU *(HostToDevice)*
3. `Kernel<<<1, N>>>`: Kernel execution
4. `cudaMemcpy`: Transfer results from GPU to CPU *(DeviceToHost)*
5. `cudaFree`: Deallocate GPU memory

Example: Array addition

```
for (int i = 0; i < N; i++) { C[i] = A[i] + B[i]; } // sequential
(i = 0 .. N-1): C[i] = A[i] + B[i]; // parallel using n threads
```

CUDA Kernel

A kernel is a function that is executed n times in parallel by m different CUDA threads.

```
// kernel definition on GPU
__global__
void VectorAddKernel(float *A, float *B, float *C) {
  int i = threadIdx.x; C[i] = A[i] + B[i];
}
// kernel invocation on CPU
VectorAddKernel<<<1, N>>>(A, B, C); // N is amount of threads
```

Only the GPU knows when the task is finished.

Boilerplate Orchestration Code

```
void CudaVectorAdd(float* h_A, float* h_B, float* h_C, int N) {
  size_t size = N * sizeof(float);
  float *d_A, *d_B, *d_C; // data on GPU
  cudaMalloc(&d_A, size); cudaMalloc(&d_B, size); cudaMalloc(&d_C, size);
  cudaMemcpy(d_A, h_A, size, cudaMemcpyHostToDevice);
  cudaMemcpy(d_B, h_B, size, cudaMemcpyHostToDevice);
  VectorAddKernel<<<1, N>>>(d_A, d_B, d_C, N);
  cudaMemcpy(h_C, d_C, size, cudaMemcpyDeviceToHost);
  cudaFree(d_A); cudaFree(d_B); cudaFree(d_C);
}
```

8.5. PERFORMANCE METRICS

The performance is either limited by *memory bandwidth* or *computation*. **Compute Bound:** Throughput is limited by calculation *(Cores are at the limit, but the memory bus could transfer more data)*. *This is better and reached if AI Kernel > AI GPU*.

Memory Bound: Throughput is limited by data transfer *(Memory bus bandwidth is at its limit, but cores could process more data)*.

Arithmetic intensity: Defined as FLOPS *(Floating Point Operations per Second)* per Byte. The higher, the better.

$$\frac{\text{Number of operations}}{\text{Number of transferred bytes}} = \frac{\text{FLOPS}}{\text{Bytes}}$$

Example `for(i=0; i<N, i++) { z[i] = x[i] + y[i] * x[i]; }` Read x and y from memory, write z to memory. That's 2 reads and 1 write *(x is used twice but read only once)*. In case x, y and z are ints, we have 12 $(3 \cdot 4)$ bytes transferred and 2 arithmetic ops ($+$, $*$). The arithmetic intensity is therefore $\frac{2}{12} = \frac{1}{6}$.

Compute Bound

- $t_{compute} > t_{memory}$
- $\frac{\#ops}{BW_{compute}} > \frac{\#bytes}{BW_{memory}}$
- $\frac{\#ops}{\#bytes} > \frac{BW_{compute}}{BW_{memory}}$

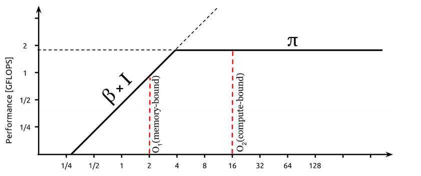
Memory Bound

- $t_{compute} < t_{memory}$
- $\frac{\#ops}{BW_{compute}} < \frac{\#bytes}{BW_{memory}}$
- $\frac{\#ops}{\#bytes} < \frac{BW_{compute}}{BW_{memory}}$

8.5.1. Roofline model

Provides performance estimates of a kernel running on differently sized architectures. Has three parameters: Peak performance, peak bandwidth vs. arithmetic intensity.

Peak performance is derived from benchmarking FLOPS or GFLOPS *(Giga-FLOPS, 10^9 FLOPS)*. The *peak bandwidth* from manuals of the memory subsystem. The *ridge point* is where the horizontal and diagonal lines meet = minimum AI required to achieve the peak performance.



9. GPU ARCHITECTURE

Because there are so *many cores* on GPUs, it is possible to run many threads in parallel *without context switches*. This allows better parallelism without a performance penalty.

9.1. COMPILATION

Just-in-time Compilation: The *NVCC compiler* compiles the non-CUDA code with the host C compiler and translates code written in CUDA into *PTX instructions* *(assembly language represented as ASCII text)*. The graphics driver compiles the PTX into *executable binary code*. The assembly of PTX code is *postponed until application runtime*, at which time the target GPU is known. The *disadvantage* of this is the *increased application startup delay*. However, thanks to cache this only happens once *(warmup)*.

Programming Interface: *Runtime* *(The cudart library provides functions that execute on the host to (de-)allocate device memory, transfer data etc.)* or *driver API* *(The CUDA driver API is implemented in the `cuda.dll` or `cuda.so` which is copied on the system during installation of the driver. This provides an additional level of control by exposing lower-level concepts such as CUDA contexts. Often overkill)*.

Asynchronous Execution: The command pipeline in CUDA works asynchronous, commands and data can be transferred from/to the GPU at the same time.

9.2. CUDA SIMT EXECUTION MODEL

Single instruction, multiple Threads. The kernel is executed N times in parallel by N different CUDA threads.

Blocks: Threads are *grouped* in blocks. The host can define how many threads each block has *(up to 1024)*. Threads in one block can *interact* with each other but not with threads in other blocks.

Execution Model: *One thread* runs on *one virtual scalar processor* *(one GPU core)*. *One block* runs on *one virtual multi-processor* *(one GPU Streaming Multiprocessor)*. Blocks must be *independent*.

Thread Pool Abstraction: The compiled CUDA program has e.g. 8 CUDA blocks. The *runtime* can *choose how to allocate* these blocks to multiprocessors. For a larger GPU with 8 SMs, each SM gets one CUDA block. This enables performance scalability without code changes.

Guarantees: CUDA guarantees that *all threads in a block* run on the *same SM* at the *same time* and that the blocks in a kernel *finish before* any block from a new, *dependent kernel* is *started*.

Mapping: One SM can run several *concurrent* blocks depending on the resources needed. Each *kernel* is executed *on one device*. CUDA supports running *multiple kernels on a device* at one time.

9.3. CUDA KERNEL SPECIFICATION

Specifying Kernel: `VectorAddKernel<<<GRID_dimension, BLOCK_dimension>>>(A,B,C)`
Dimensions can be 1D, 2D or 3D and specified via `dim3` which is a structure designed for storing block and grid dimensions: `struct dim3{x; y; z}`.

`dim3 dimGrid(2) == dim3 dimGrid(2,1,1)` *(Unassigned components are set to 1)*
`VectorAddKernel<<<dimGrid, dimBlock>>>(A,B,C);`
Number of blocks in a grid: `dimGrid.x * dimGrid.y * dimGrid.z`
Number of threads in a block: `dimBlock.x * dimBlock.y * dimBlock.z`

1D Grid: We can simply use integers. `VectorAddKernel<<<1, N>>>` creates 1 Block with N Threads.

2D Grid: `dim3 gridS(3,3); dim3 blockS(3,3); VectorAddKernel<<<gridS, blockS>>>`

3D Grid: `dim3 gridS(3,2,1); dim3 blockS(4,3,1); VectorAddKernel<<<gridS, blockS>>>`

Device Limits: *Max threads per block:* 1024, *Max thread dimensions per block:* (1024, 1024, 64)
Max grid size: (2'147'483'647, 65'535, 65'535)

Calculation Examples

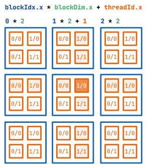
```
VectorAddKernel<<<dim3(8,4,2),
dim3(16,16)>>>(d_A, d_B, d_C);
```

Amount of Blocks: $8 \cdot 4 \cdot 2 = 64$
Amount of threads per block: $16 \cdot 16 = 256$
Threads in total: $64 \cdot 256 = 16'384$

If we have 1024 threads in a block, how many blocks are needed to launch N threads?

`int blocksPerGrid = (N + threadsPerBlock - 1) / threadsPerBlock;`

Need to round up because for 1025 threads we need 2 blocks


blockIdx.x * blockDim.x + threadId.x
0 * 2
1 * 2 + 1
2 * 2
blockIdx.y * blockDim.y + threadId.y
0 * 2
1 * 2 + 0
2 * 2
0/0
1/0
0/1
1/1

9.4. DATA PARTITIONING WITHIN THREADS

Data Access: Each kernel decides which data to work on. The programmers decide data partitioning scheme. `threadId.x/y/z` *(Thread no. in block)*, `blockId.x` *(Block no.)*, `blockDim.x` *(Block size)*

Partitioning in Blocks:

```
__global__
void VectorAddKernel(float *A, float *B, float *C) {
  int i = blockIdx.x * blockDim.x + threadIdx.x; //index based on (blockID, threadID)
  if (i < N) {
    C[i] = A[i] + B[i]; // without this if, some threads will be idle
  }
}
// kernel invocation
N = 4097; int blockSize = 1024; int gridSize = (N + blockSize - 1) / blockSize;
VectorAddKernel<<<gridSize, blockSize>>>(A, B, C);
```

Boundary Check: More threads than necessary work on the data. If N = 4097, 5 Blocks with 1024 Threads are needed which results in *1023 unused threads*. Threads with $i \geq N$ must *not be allowed* to write to array C because they might *corrupt the working memory* of some other thread.

9.5. ERROR HANDLING

Some functions have return type `cudaError`. Need to check for `cudaSuccess`. It's best to write your own helper function and wrap *every fucking line* in it. E.g. `handleCudaError()` which prints the error and exits the program.

9.6. UNIFIED MEMORY

Unified memory allows automatic transfer from CPU to GPU and vice versa. No explicit Memory Copy needed, but other new rules.

```
cudaMallocManaged(&A, size); // ... same for &B and &C ...
A[0] = 8; ... // initialize A and B assuming they reside on the host
// A and B are automatically transferred to the device
VectorAddKernel<<<..,..>>>(A,B,C,N);
cudaDeviceSynchronize(); // wait for the GPU to finish
// C is transferred automatically to the host and can be read directly
std::cout << C[0]; ...
cudaFree(A); cudaFree(B); cudaFree(C);
```

10. GPU PERFORMANCE OPTIMIZATIONS

Hardware: A scalable array of multithreaded *Streaming Multiprocessors* (SMs), the *threads* of a thread block execute *concurrently* on one multiprocessor, multiple *thread blocks* can execute *concurrently* on one multiprocessor. When thread blocks *terminate*, new blocks are launched on the free multiprocessors.

10.1. MATRIX ADDITION

```
__global__
void MatrixAddKernel(float *A, floa *B, float *C) {
  int column = blockIdx.x * blockDim.x + threadIdx.x;
  int row = blockIdx.y * blockDim.y + threadIdx.y;
  if (row < A_ROWS && col < A_COLS) { // boundary checking
    C[row * A_COLS + col] = A[row * A_COLS + col] + B[row * A_COLS + col];
  }
}
const int A_COLS, B_COLS, C_COLS = 6;
const int A_ROWS, B_ROWS, C_ROWS = 4;
dim 3 block = (2,2); dim3 grid = (3,2);
MatrixAddKernel<<<grid,block>>>(A,B,C);
```

10.2. MATRIX MULTIPLICATION

Parallelization: Every Thread computes one element of the result matrix C. Can be parallelized because results do not depend on each other.

```
__global__
void multiply(float *A, floa *B, float *C) {
  int i = blockIdx.x * blockDim.x + threadIdx.x;
  int j = blockIdx.y * blockDim.y + threadIdx.y;
  if (i < N && j < M) { // boundary checking
    float sum = 0;
    for (int k = 0; k < K; k++) {
      sum += A[i * K + k] * B[k * M + j];
    }
    C[i * M + j] = sum;
  }
}
```

10.3. MAPPING THREADS / BLOCKS TO GPU WARPS

Warps: Blocks are split into *warps* *(1 Warp = 32 Threads)* and all threads within execute the same code. If there aren't enough threads to fill a warp, "empty" threads are launched. A number of warps constitutes a *thread block*. A number of *thread blocks* are assigned to a *Streaming Multiprocessor*. The whole GPU consists of several SM.

Thread blocks are scheduled in *parallel* or *sequentially*. Once a thread block is *launched* on a SM, *all of its warps are resident* until their execution finishes. Therefore, a *new block on a SM* is *not launched until* there is a *sufficient number* of free registers and shared memory for *all warps* of the new block.

Warp Execution: All threads in a warp execute the same instruction *(SIMD)*. A SM can accommodate all warps of a block, but only *a subset* is *running in parallel* at the same time *(1 to 24)*.

Divergence: *Not* all threads of a warp may *branch the same way*. The branches do *not run simultaneously*, so the other threads need to *wait* until one branch is finished. So branches within one warp should be *avoided* because of *performance problems* *(Branches are born at `if` / `switch` / ...)*

```
// bad case, divergence in same wrap     // good case, all t in warp in same branch
if (threadIdx.x > 1) { } else {  }      if (threadIdx.x / 32 > 1) { } else { }
```

DRAM (Dynamic Random Access Memory): *Global memory of a CUDA device* is implemented with DRAMs. If a GPU kernel accesses data from *consecutive locations*, the DRAMs can supply the data at a much *higher rate* than if a random sequence of locations were accessed.

Memory Coalescing: Thread *access patterns* are critical for performance. If the threads in a warp *simultaneously* access *consecutive memory locations*, their reads can be combined into a single access *(burst)*. Else there are *expensive individual accesses*.

Coalesced Accesses: Read/Write the burst in one transaction per warp burst section, swapped read/write within the same burst, only individual elements in the burst accessed.

Not Coalesced Accesses: Read/Write in different warp bursts, one action that spans multiple bursts.

Coalescing in Use: *`data[(Expression without threadId.x) + threadId.x]`*

Coalescing with Matrices: Matrices get linearized to a 1D array. The row of the matrix should be the longer side so that there are as many coalescing accesses as possible.

10.4. MEMORY MODEL

All threads have the access to the same *global memory*. Each thread block has *shared memory* visible to all threads of the block and with the same lifetime as the block *(Has higher bandwidth and lower latency than local or global memory but longer latency and lower bandwidth than registers which are private to a thread)*. Each thread has *private local memory* *(in device memory, high latency and low bandwidth, same as global)*. Constant, texture and surface memory also reside in device memory.

Memory Hierarchy: *Shared Memory* *(per SM, fast, shared between threads in 1 block, a few KB, `__shared__ float x`)*, *Global Memory* *("Main Memory" in GPU Device, slow, accessible to all threads, in GB, `cudaMalloc()`)* *Registers* *(private to a thread, fastest but very limited storage)*

Constant memory: Constant variables are stored in the *global memory* but are *cached*.

Shared Memory Declaration: With keyword `__shared__`. A *static array size* is necessary. Limited memory, around 48KB. Multidimensionality is allowed.

Fast Matrix Multiplication: By *reducing global memory traffic*. Partition data into subsets called tiles which fit into shared memory *(the row & column that should be multiplied and the result cell)*. The kernel computation on these tiles must be able to run *independently* of each other. Because the shared memory is *limited*, load the tiles in *several steps* and calculate the *intermediate result* from this.

```
__global__ void MatrixMulKernel(float* d_M, float* d_N, float* d_P, int Width) {
  __shared__ float Mds[TILE_WIDTH][TILE_WIDTH];
  __shared__ float Nds[TILE_WIDTH][TILE_WIDTH];
  int bx = blockIdx.x; int by = blockIdx.y;
  int tx = threadIdx.x; int ty = threadIdx.y;
  // identify row and column of the d_P element to work on
  int Row = by * TILE_WIDTH + ty;
  int Col = bx * TILE_WIDTH + tx;
  float Pvalue = 0;
  // loop over d_M and d_N tiles required to compute d_P element
  for (int m = 0; m < Width/TILE_WIDTH; ++m) {
    // collaborative loading of d_M and d_N tiles into shared memory
    Mds[ty][tx] = d_M[Row*Width + m*TILE_WIDTH + tx];
    Nds[ty][tx] = d_N][(m*TILE_WIDTH + ty)*Width + Col];
    __syncthreads(); // CUDA equivalent to wait()
    for (int k = 0; k < TILE_WIDTH; ++k) {
      Pvalue += Mds[ty][k] * Nds[k][tx];
    }
    __syncthreads();
  }
  d_P[Row*Width + Col] = Pvalue;
}
```

`__syncThreads()` is only allowed in `if/else` if all threads of a block choose the same branch, otherwise undefined behavior.

11. HIGH PERFORMANCE COMPUTING (HPC) CLUSTER PARALLELIZATION

Cluster programming is the *highest possible parallel acceleration* *(Factor 100 and more)*. Used for *general purpose programming*, lots of CPU cores. Combination of CPUs and GPUs possible.

Computer Cluster: Network of *powerful* computing nodes, firmly connected at one location. Very *fast interconnect* *(like 100GBit/s)*, used for big simulations *(Fluids, Weather, Traffic, etc.)*

SPMD: This is the most commonly used programming model, "high level". *Single Program* *(All tasks execute their copy of the same program simultaneously)*, *Multiple Data* *(all tasks may use different data)*. The MPI program is started in several processes. All processes start and terminate synchronously. Synchronization is done with barriers.

MPMD: Also a "high level" programming model. *Multiple Program* *(Tasks may execute different programs simultaneously)*, *Multiple Data* *(all tasks may use different data)*.

Hybrid Memory Model: All processors in a machine can *share* the memory. They also can *request* data from other computers. *(non-uniform memory access: not all accesses take the same time)*

Message Passing Interface (MPI): Distributed programming model. Is a common choice for Parallelization on a cluster, Industry-Standard libraries for multiple programming languages.

MPI Model: Notion of processes *(Process is the running program plus its data)*, parallelism is achieved by running *multiple processes*, co-operating on the *same* task. Each process has *direct access* only to its *own data* *(variables are private)*. Inter-Process-Communication by sending and receiving messages.

SPMD in MPI: All processes run their *own local copy* of the program & data. Each process has a *unique identifier*, processes can take *different paths* through the program depending on their IDs. Usually, *one process per core* is used *(to maximize the benefit of parallelization)*.

Formalizing Message: A message transfers a number of data items from the memory of one process to the memory of another process *(Typically contains ID of sender and receiver, data type to be sent, number of data items, data itself, message type identifier)*.

Communication modes: *Point to Point* *(very simple, one sender and one receiver. Relies on matching send and receive calls)* and *Collective communications* *(between groups of processes. Broadcast: one to all, Scatter: Split data and send each chunk to different node, Gather: Collect the chunks back at the originating node)*.

11.1. MPI BOILERPLATE CODE

```
int main(int argc, char * argv[]) {
  MPI_Init(&argc, &argv); // MPI Initialization
  int rank; int len;
  MPI_Comm_rank(MPI_COMM_WORLD, &rank); // Process Identification
  char name[MPI_MAX_PROCESSOR_NAME];
  MPI_Get_processor_name(name, &len);
  printf("MPI process %i on %s\n", rank, name);
  MPI_Finalize(); // MPI Finalization
  return 0; }
```

`MPI_Init`: Must be the *first* MPI call. Allows the `mpi_init` to broadcast to all the processes. Does *not* create processes, they are only created at launch time. All MPI *global and internal variables are constructed*. A *communicator* is formed around all the processes that were spawned and *unique ranks* *(IDs)* are assigned to each process. *`MPI_COMM_WORLD`* encloses all processes in the job.

Communicator: Group of MPI processes, allows inter-process-communication.

`MPI_Comm_rank`: *Returns the rank* of a process in a communicator. Used for sender/receiver IDs.

`MPI_Comm_size`: *Returns the total number* of processes in a communicator.

`MPI_Finalize`: Is used to *clean up* the environment. No more MPI calls after that.

`MPI_Barrier`: Blocks until all processes in the communicator have reached the barrier. **Compilation & Execution:** `mpicc HelloCluster.c && mpiexec -c 24 a.out && sbatch -hi.sub`

Process Identification: *Rank* = number within a group, incremental numbering from 0. Unique Identification = (Rank, Communicator)

```
MPI_Send(void * data, int count, MPI_Datatype datatype, int destination, int tag,
MPI_Comm communicator) // tag: freely selectable number for msg type (⩾ 0)

MPI_Recv(void * data, int count, MPI_Datatype datatype, int source, int tag, MPI_Comm
communicator, MPI_Status* status) // status: error information
```

Each *send* should have a matching *receive*.

Example direct communication:

```
MPI_Send(&value, 1, MPI_INT, receiverRank, tag, MPI_COMM_WORLD);
MPI_Recv(&value, 1, MPI_INT, senderRank, tag, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
```

Array send: `int array[LENGTH];`

```
MPI_Send(array, LENGTH, MPI_INT, receiverRank, tag, MPI_COMM_WORLD);
MPI_Recv(array, LENGTH, MPI_INT, senderRank, tag, MPI_COMM_WORLD, MPI_STATUS_IGN);
```

`MPI_Bcast`: Is *efficient*, because the root node does *not send the signal individually* to each node, the *other nodes help* spread the message to others. *(signal spreads like corona)*: `MPI_Bcast(void * data, int count, MPI_Datatype datatype, int root, MPI_Comm_World communicator)`

`MPI_Reduce`: Reduction is a classic concept: reducing a set of numbers into a smaller set of numbers via a function *(e.g. `[1,2,3,4,5]` ⇒ sum ⇒ 15)*. Each process contains one integer, `MPI_Reduce` is called with a root process of 0 and using `MPI_SUM` as the reduction operation. The four numbers are added and stored on the root process. Job is done in a *distributed manner*.

`MPI_Reduce(void* send_data, void* recv_data, int count, MPI_Datatype datatype, MPI_Op op, int root, MPI_Comm comm)` *(`send_data`: array of elements of type `datatype` to reduce from each process, `recv_data`: relevant on the root process. contains the reduced result and has a size of `sizeof(datatype) * count`. `op` the operation you wish to apply to your data: MPI_MAX, MPI_MIN, MPI_SUM, MPI_PROD: multiplies all, MPI_BAND/MPI_LAND: Bitwise/Logical AND, MPI_LOR: Logical OR, MPI_MAXLOC: Same as max plus rank of process that owns it)*

`MPI_AllReduce`: Many parallel applications require accessing the reduced results *across all processes*. This function reduces the values and distributes the result to all processes. Does not need a root node. This is an *implicit broadcast* to all processes.

```
MPI_Allreduce(void* send_data, void* recv_data, int count, MPI_Datatype datatype,
MPI_Op op, MPI_COMM comm)
```

`MPI_Gather`: Gather together multiple values from different processors.

```
MPI_Gather(&input_value, 1, MPI_INT, &output_array, 1, MPI_INT, 0, MPI_COMM_WORLD)
```

11.2. APPROXIMATION OF π VIA MONTE CARLO SIMULATION

Draw a circle inside of a square and randomly place dots in the square. The ratio of dots inside the circle to the total number of dots will approximately equal $\frac{\pi}{4}$.

```
// Sequential
long count_hits(long trials) { long hits = 0, i; for (i = 0; i < trials; i++) {
    double x = (double)rand()/RAND_MAX; double y = (double)rand()/RAND_MAX;
    if (x * x + y * y ⩽ 1) { hits++;} // distance to center is bigger than radius=1
  } return hits; }

//Parallel, the trials are split across different nodes
int rank, size;
MPI_Comm_rank(MPI_COMM_WORLD, &rank); MPI_Comm_size(MPI_COMM_WORLD, &size);
srand(rank * 4711); // each process receives a different seed
long hits = count_hits(TRIALS / size); // Each process computes a subtask
long total;
MPI_Reduce(&hits, &total, 1, MPI_LONG, MPI_SUM, 0, MPI_COMM_WORLD);
if (rank == 0) { double pi = 4 * ((double)total / TRIALS); }
```

12. OPENMP

Node: A standalone *"computer in a box"*. Usually comprised of multiple CPU/processors/cores, memory, network interfaces etc. Nodes are *networked together* to comprise a *supercomputer*. Each node consists of 20 cores. The processes do *not share memory*, they must use messages.

Threads: Default are 24 on a single Node in OST cluster. Can be set with `omp_set_num_threads()` or with the `OMP_NUM_THREADS` environment variable. Threads range from 0 *(master thread)* to N-1.

HPC Hybrid memory model: Run a program on multiple nodes. No Shared Memory *(NUMA)* between Nodes. Shared Memory *(SMP)* for Cores inside a Node.

OpenMP: Is a programming model for different languages. *Allows to run multiple threads*, distribute work using synchronization and reduction constructs. *Shared Memory* *(shared memory process consists of multiple threads)*, *Explicit Parallelism* *(Programmer has full control over parallelization)* and *Compiler Directives* *(Most OpenMP parallelism is specified through the use of compiler directives (`pragmas`) in the source code)*.

Fork and Join

```
#include <stdio.h>
#include <omp.h>
int main(int argc, char* argv[]) {
  const int np = omp_get_max_threads(); // executed by initial thread
  printf("OpenMP with threads %d\n", np); // executed by initial thread
  #pragma omp parallel // pragma spawns multiple threads (fork)
  {
    const int np = omp_get_num_threads(); // executed in parallel
    printf("Hello from thread %d\n", omp_get_thread_num()); // executed in parallel
  } // order not fixed. after execution, threads synchronize and terminate.
  return 0; }
```

For loops

```
#pragma omp parallel for
  for (i=0; i<n; i++) { ... }
```

Each thread processes *one loop-iteration* at a time. Execution returns to the initial threads. *Oversubscription* *(too many threads for a problem)* is handled by OpenMP. The iteration variable *(i.e. i)* is implicitly made private for the duration of the loop.

Memory Model

```
int A, B, C //automatically global because outside of pragma
#pragma omp parallel for private (A) shared (B) firstprivate (C)
  for(...)
```

Each thread has a *private copy of A* and use the *same memory location for B*. C is also private, but gets its initial value from the global variable. After the loop is over, threads die and both A and B will be cleared/removed from memory.

```
#pragma omp parallel
  int A = 0 // automatically private because inside of pragma
#pragma omp for ...
```

Avoiding Race conditions: Mutex

```
int sum = 0;
#pragma omp parallel for
  for (int i = 0; i < n; i++)
#pragma omp critical { sum += i; } // only one thread at a time
```

This is *extremely slow* due to serialization, slower than single threading. Critical section is *overkill* for this code, with a heavy weight mutex the performance overhead is large.

Lightweight mutex: Atomic

```
int sum = 0; int i;
#pragma omp parallel for
  for (i = 0; i < n; i++)
  #pragma omp atomic { sum += i }
```

Reduction across threads

When using `reduction(operator: variable)`, a *copy* of the reduction variable per thread is created, initialized to the identity of the reduction operator ($+ = 0, * = 1$). Each thread will then *reduce* into its local variable. At the end of the `parallel` region, the local results are *combined into the global variable*. Only associative operators allowed ($+, *$, not $-, /$).

```
// Code using the reduction clause
int sum = 0;
#pragma omp parallel for reduction(+: sum)
  for (int i = 0; i < n; i++) { sum += i; }

// The same code without the reduction clause
int sum = 0;
#pragma omp parallel {
  int intermediate_sum = 0; // private
  #pragma omp for
    for (int i = 0; i < n; i++) { intermediate_sum += i; } // thread partial sum
  #pragma omp atomic // reduction is protected with atomic
    final_sum += intermediate_sum; }
```

Hybrid: OpenMP + MPI

```
int numprocs, rank; int iam = 0, np = 1;
MPI_Init(&argc, &argv);
MPI_Comm_size(MPI_COMM_WORLD, &numprocs);
MPI_Comm_rank(MPI_COMM_WORLD, &rank);
#pragma omp parallel default(shared) private(iam, np) {
  np = omp_get_num_threads();
  iam = omp_get_thread_num();
  printf("I am T %d out of %d from P %d out of %d\n", iam, np, rank, numprocs);
} MPI_Finalize();
```

Sequential `count_hits` to approximate π with Monte Carlo Simulation in OpenMP

```
long count_hits(long trials) {
  long hits = 0; long i; double x,y;
  #pragma omp parallel {
    #pragma omp for reduction(+:hits) private(x,y)
      for (i = 0; i < trials; i++) {
        double x = random_double(); double y = random_double();
        if (x * x + y * y ⩽ 1) { hits++; }
      }}
  return hits; }
```

13. PERFORMANCE SCALING

Difficulties with parallel programs: Finding parallelism, granularity of a parallel task, moving data is expensive, load balancing, coordination & synchronization, performance debugging.

Scalability: The ability of hard- and software to deliver *greater computational power* when the number of *resources is increased*.

Scalability Testing: Primary challenge of parallel computing is *deciding how best to break up a problem* into individual pieces that can be computed separately. It is *impractical* to develop and test large applications using the *full problem size*. The problem and number of processors are *scaled down* at first. *Scalability testing:* measuring the ability of an application to perform well or better with varying problem sizes and numbers of processors. It does *not* test the applications *general functionality* or correctness.

13.1. STRONG SCALING

The number of processors is increased while the problem size remains constant. Results in a reduced workload per processor. Mostly used for long running CPU bound applications.

Amdahls Law: The speedup is *limited by the fraction of the serial part* of the software that is not amenable to parallelization. Sweet spot needs to be found. It is reasonable to use *small amounts of resources for small problems* and *larger quantities of resources for big problems*.

T = total time, p = part of the program that can be parallelized., N = amount of processors

$T = (1-p)T + T_p = T_s + T_p$

$T_N = T_p/N + (1-p)T$, Speedup $\leq 1/(s + p/N)$, Efficiency $= T/(N \cdot T_N)$

Amdahls law *ignores the parallel overhead*. Because of that, it is *the upper limit* of speedup for a problem of fixed size. This seems to be a *bottleneck* for parallel computing.

Examples: 90% of the computation can run parallel, what is the max speedup with 8 processors?

$1/(0.1 + 0.9/8) \approx \underline{4.7}$

25% of the computation must be serial. What is the max speedup with ∞ Processors?

$1/(0.25 + 0.75/\infty) \approx 1/0.25 = 4$

To gain a $500\times$ speedup on 1000 processors, Amdahls law requires that the proportion of serial part cannot exceed what?

$500 = 1/(s + \frac{1-s}{1000}) \Rightarrow s + \frac{1-s}{1000} = \frac{1}{500} \Rightarrow 1000s + (1-s) = 2 \Rightarrow 999s = 1 \Rightarrow s = \frac{1}{999} \approx \underline{0.1\%}$

13.2. WEAK SCALING

The number of processors and the problem size is increased. Mostly used for large *memory-bound* applications where the required memory cannot be satisfied by a single node.

Gustafson's law: Based on the approximations that the *parallel part scales linearly* with the amount of resources, and that the *serial part* does *not increase* with respect to the size of the problem. *Speedup* $= s + p \cdot N = s + (1-s) \cdot N$

In this case, the problem size assigned to each processing element stays *constant* and *additional elements* are used to solve a *larger total problem*. Therefore, this type of measurement is justification for programs that take a lot of memory or other system resources.

Example: 64 Processors. 5% of the program is serial. What is the scaled weak speedup?

$0.05 + 0.95 \cdot 64 = \underline{60.85}$