1 Course Overview

- Even though Moore's Law[1] is still valid, heat and power are of primary concerns.
  - These challenges can be overcome with smaller and more efficient processors or simply more processors
  - To make better use of the added computation power, parallelism is used.
- Parallel vs. Concurrent: In both cases, one of the difficulties is to actually determine which processes can overlap and which can't:
  - Concurrent: Focus on which activities may be executed at the same time (= overlapping execution)
  - Parallel: Overlapping execution on a real system with constraints imposed by the execution platform.
- Parallel/Concurrent vs. distributed: In addition to parallelism/concurrency, systems can actually be physically distributed (e.g. BOINC)
- Concerns in PP:
  - Expressing Parallelism
  - Managing state (data)
  - Controlling/coordinating parallel tasks and data

2 Parallel Architectures

- Turing machine:
  - Infinite tape
  - Head that reads/writes symbols on tape
  - State registers
  - Program is expressed as rules: (reg)(head) $\rightarrow$ (reg)(head)(movement)
- Today's computers:
  - Consist of CPU, memory and I/O
  - Stored Program: program instructions are stored in memory
  - Von Neumann Architecture: Program data and program instruction in the same memory
- Since accessing memory became slower than accessing CPU registers, CPUs now have caches which are closer (faster and smaller) to the CPU. Caches are:
  - Faster then memory
  - Smaller than memory

[1] "The number of transistors on integrated circuits doubles approximately every two years"

  - Organized in multi-level hierarchies (e.g. L1,L2,L3)

- To improve sequential processor performance, you can use the following parallelism techniques:
  - Vectorization
    For example, when adding vectors (load → operation(s) → store)
    * Normal: 1-at-a-time
    * Vectors: N-at-a-time (bigger registers)
  - Pipelining[2]

    * Multiple stages (CPU Functional Units)
      · Instruction Fetch
      · Instruction Decode
      · Execution
      · Data access
      · Writeback
    * Each instruction takes 5 time units (cycles)
    * 1 instruction per cycle (not always possible though)
  - Instruction Level Parallelism (ILP)
    * Superscalar CPUs
      · Multiple instructions per cycle
      · multiple functional units
    * Out-of-Order (OoO) Execution
      · Potentially change execution order of instructions
      · As long as the programmer observes the sequential program order
    * Speculative execution
      · Predict results to continue execution

- Moore's Law
  - *"The number of transistors on integrated circuits doubles approximately every two years"* - Gordon E.Moore, 1965
  - Actually an observation
  - For a long time, CPU Architects improved sequential execution by exploiting Moore's Law and ILP

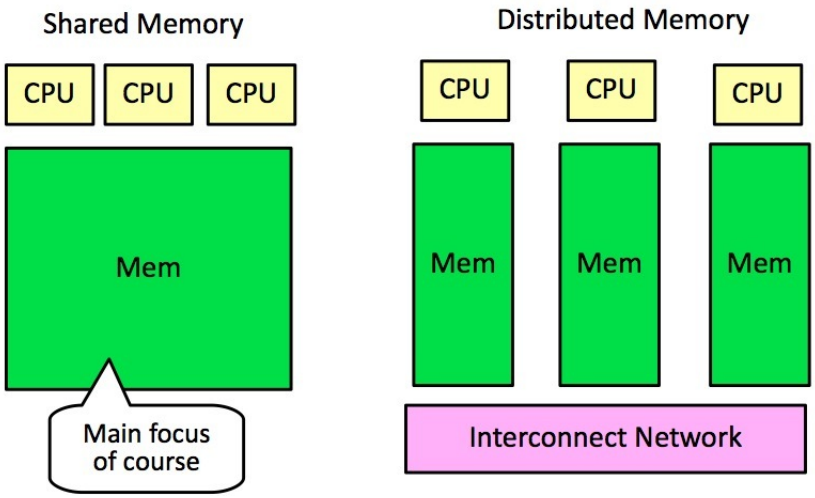
[2]Think laundry: you can either wash, dry, fold and repeat, or while the n load is drying, the $n+1$ load can start washing

  - More transistors → more performance
  - Sequential programs were becoming exponentially faster with each new CPU
    * (most) programmers did not worry about performance
    * They waited for the next CPU model

- Architects hit walls
  - Power dissipation wall: Making CPU faster → expensive to cool
  - Memory Wall: CPUs faster than memory access
  - ILP Wall: Limits in inherent program's ILP, complexity
  - **No longer affordable to increase sequential CPU performance**

- Multicore processors
  - Use transistors to add cores (instead of improving sequential performance)
  - Expose parallelism to software
  - Implication: Programmers need to write parallel programs to take advantage of new hardware
    * Past: Parallel programming was performed by a few
    * Now: Programmers need to worry about (parallel) performance

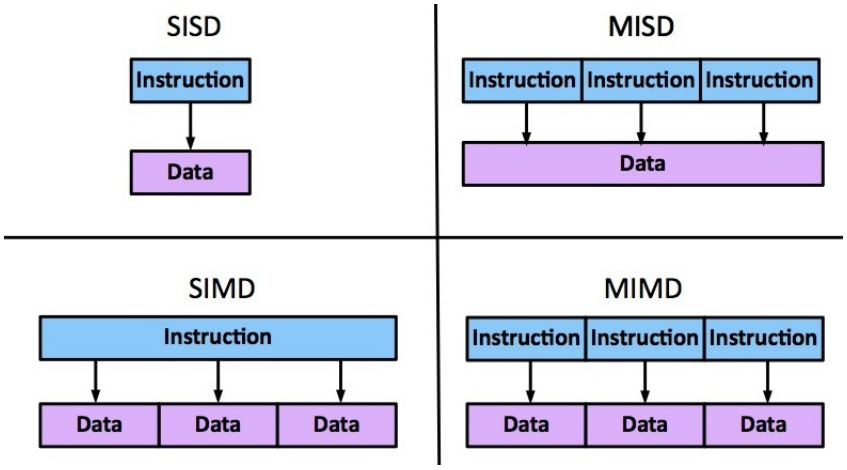
- Shared memory architectures



  - SMT (Hyperthreading)
    * Single core
    * Multiple instruction streams (threads); Virtual (phony) cores
    * Between ILP ↔ multicore
      · ILP: Multiple units for one instruction stream

        - SMT: Multiple units for multiple instruction streams
    - Limited parallel performance
  - Multicores
    - Single chip, multiple cores
    - Dual-, Quad-, x8...
    - Each core has its own hardware units; computations un parallel perform well
    - Might share part of the cache hierarchy
  - SMP (Symmetric MultiProcessing)
    - Multiple CPUs on the same system
    - CPUs share memory: same cost to access memory
    - CPU caches coordinate: Cache coherence protocol
  - NUMA (Non-Uniform Memory Access)
    - Memory is distributed
    - Local/Remote (fast/slow)
    - Shared memory interface

- Flynn's Taxonomy



- GPUs
  - Graphical Processing Units
    - SIMD
    - Scene description → pixels
    - Highly data-parallel process
  - Massively parallel vector machines
  - Not a standard component up until recently
  - Started very specialized (rigid pipelines)
  - Driven by game industry success

- GP-GPUs
  - General programming using GPUs (CUDA, OpenCL)
  - Much research on "how to execute X on a GPU"
  - Generally GPUs are:
    * Well suited for data parallel programs
    * Not very well-suited for programs with random accesses
    * People are rethinking algorithms
  - GPUs are, currently, something of a standard in the HPC (High Performance Computing) domain

3 Basic Concepts

- Performance in sequential execution:
  - Computational complexity
    * Theoretical computer science
    * Asymptotic behavior: big O notation ($\mathcal{O}$), or big Θ
    * How many steps does an algortithm take
    * Complexity classes
  - Execution Time: The less time, the better
- Sequential programs are much easier to write, but if we care about performance we have to write parallel programs
- Parallel Performance
  - Sequential execution time: T_1
  - Execution time T_p on p CPUs:
    * $T_p = \frac{T_1}{p}$ (Perfection)
    * $T_p > \frac{T_1}{p}$ (Performance Loss, what normally happens)
    * $T_p < \frac{T_1}{p}$ (Sorcery!)
- (Parallel) Speedup
  - (Parallel) speedup S_p on p CPUs:

$$S_p = \frac{T_1}{T_p}$$

    * $S_p = p \rightarrow$ linear speedup (Perfection)
    * $S_p < p \rightarrow$ sublinear speedup (Performance loss)
    * $S_p > p \rightarrow$ superlinear speedup (Sorcery!)
  - Efficiency: $\frac{S_p}{p}$
- Scalability: How well a system reacts to increased load
  - In Parallel Programming

    - Speedup when we increase processors
    - What will happen if number of processors $\to \infty$

- Performance loss ($S_p < p$) happens because:
  - Programs may not contain enough parallelism, e.g.:
    - pipeline with 4 stages on a 32-CPU machine
    - Some parts of the program might be sequential
  - Overheads introduced by parallelization; typically associated with coordination
  - Architectural limitations, e.g. memory contention

- Amdahl's Law
  - b: sequential part (no speedup)
  - $1 - b$: parallel part (linear speedup)

$$T_p = T_1 \left(b + \frac{1-b}{p} \right) \qquad S_p = \frac{p}{1 + b\,(p-1)}$$

  - Remarks About Amdahl's Law:
    - It concerns maximum speedup (Optimistic approach). Architectural constrains will make factors worse
    - Takeaway: **All non-parallel parts of a program (no matter how small) can cause problems!**
    - Law of diminishing returns[3]

- Gustafson's Law
  - An Alternative (optimistic) view to Amdahl's Law
  - Observations:
    - Consider problem size
    - Run-time, not problem size, is constant
    - More processors allows to solve larger problems in the same time
    - Parallel part of a program scales with the problem size
  - Formula:
    - b: sequential part (no speedup)

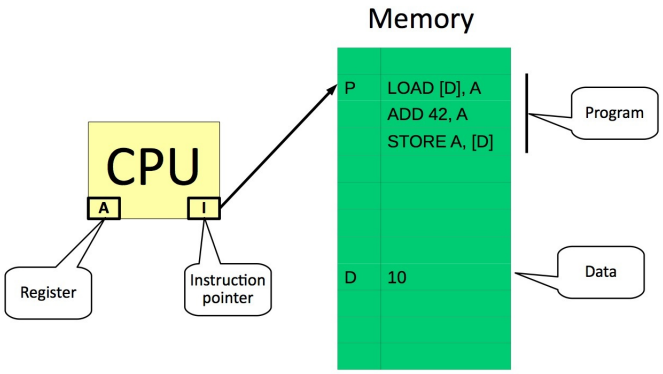
$$T_1 = p(1-b)T_p + bT_p$$
$$S_p = p - b(p-1)$$

- Concurrency vs. Parallelism
  - Concurrency is:
    - A programming model

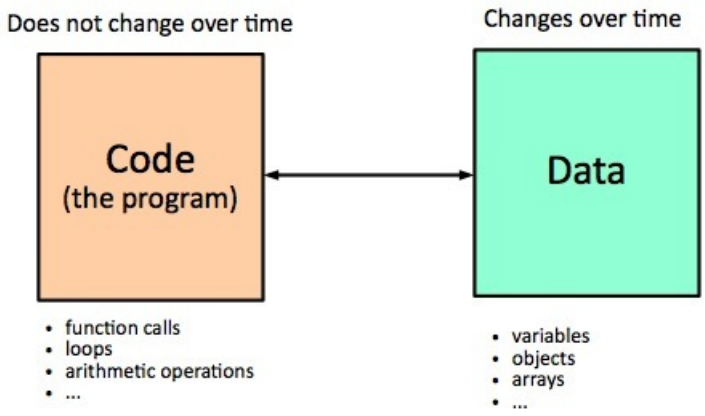
[3]The law of diminishing returns (also law of diminishing marginal returns or law of increasing relative cost) states that in all productive processes, adding more of one factor of production, while holding all others constant, will at some point yield lower per-unit returns [Taken from Wikipedia]

    - Programming via independently executing tasks
    - About structuring a program
    - A concurrent program does not have to be parallel
  - Parallelism:
    - About execution
    - Concurrent programming is suitable for parallelism

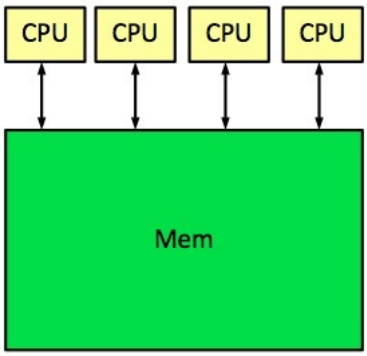
- Architectural view: CPU and Memory



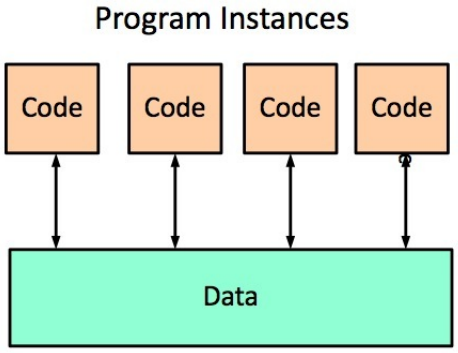
- Programmer's view: Core and Data



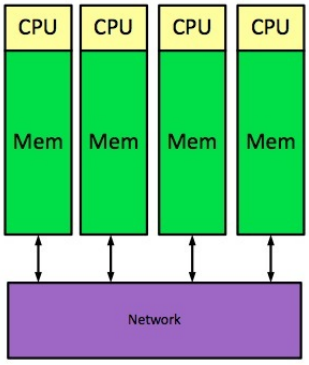
- Architectural view: Shared Memory



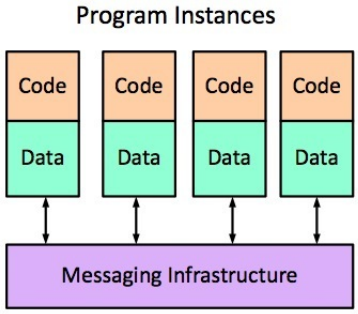
- Programmer's view: Shared Data



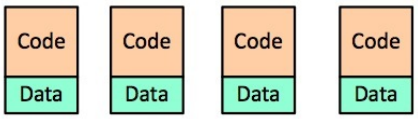
- Architectural view: Distributed Memory



- Programmer's view: Message passing

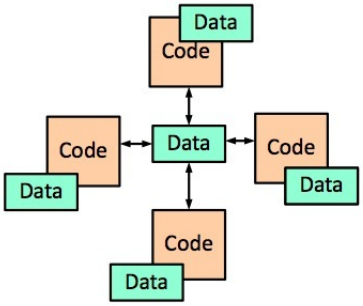


- Programmer's view: Embarrassingly Parallel



  - Each parallel part uses their own data exclusively
  - No coordination needed

- Programmer's view: non-shared & shared data



- Concerns in Parallel programming
  - Expressing parallelism
    - Work partitioning (Split up work for a single program into parallel tasks). Can be done:
      - Manually (task parallelism): User explicitly expresses tasks
      - Automatically by the system (e.g. in data parallelism): User expresses an operation and the system takes care of how to split it up
    - Scheduling
      - Assign task to processors (usually done by the system)
      - goal: full utilization (no processor is ever idle)
  - Managing state (data)

        * Shared vs. distributed memory architectures (in the latter, data needs to be distributed)
        * Which parallel tasks access which data, and how (e.g. READ or WRITE access)
        * (Potentially) split up data. Ideal: each task exclusively accesses its own data
        * Depending on the application:
            · Tasks, then data
            · Data, then tasks
    - Controlling/Coordinating parallel tasks and data
        * Distributed data
            · No coordination (e.g. embarrassingly parallel)
            · Messages
        * Shared data: controlling concurrent access
            · Concurrent access may cause inconsistencies
            · Mutual exclusion to ensure data consistency

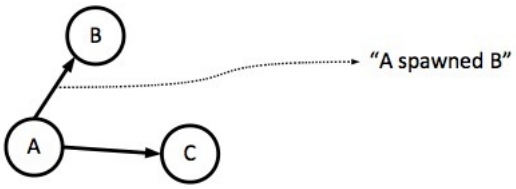
- Coarse vs. Fine Granularity
    - Fine granularity
        * More portable (can be executed in machines with more processors)
        * Better for scheduling
        * Parallel slackness (Expressed parallelism >> machine parallelism)
        * BUT: if scheduling overhead is comparable to a single task → overhead dominates
    - Guidelines:
        * As small as possible
        * but, significantly bigger than scheduling overhead; system designers strive to make overheads small
    - Coordinating tasks:
        * Enforcing ordering between tasks, e.g.:
            · Task X uses result of task A
            · Task X needs to wait for task A to finish
        * Example primitives:
            · `barrier`
            · `send()`/`receive()`
        * All tasks need to reach the barrier before they can proceed

4 Parallel programming models

- Parallel Programming is not uniform
    - Similar to sequential programming
    - Many different approaches to solve problems

- Many are equivalent under certain conditions, it depends on the application
- More of an art than a science

- Task Parallel: Programmer explicitly defines parallel tasks (generic, not always productive)
  - Tasks:
    - Execute code
    - Spawn other tasks
    - wait for results from other tasks
  - A graph is formed based on spawning tasks



  - Example: Fibonacci function

```
public class Fibonacci {
   public static long fib(int n) {
      if (n < 2)
         return n;
      spawn a task to execute fib(n-1);
      spawn a task to execute fib(n-2);
      wait for the tasks to complete
      return the addition of the task results
      }
}
```

  - Tasks can execute in parallel
    - But they don't have to
    - Assignment of tasks to CPU is up to the scheduler
  - Task graph is dynamic: unfolds as execution proceeds
  - Intuition: wide task graph → more parallelism
  - Time:

    Check for a better explanation somewhere else

  - Scheduling
    - algorithm for assigning tasks to processors
    - There exists a scheduling with

$$T_p \leq \frac{T_1}{p} + T_\infty$$

    - This upper bound can be achieved with a greedy scheduler
      1. if $\geq p$ tasks exist, p tasks execute

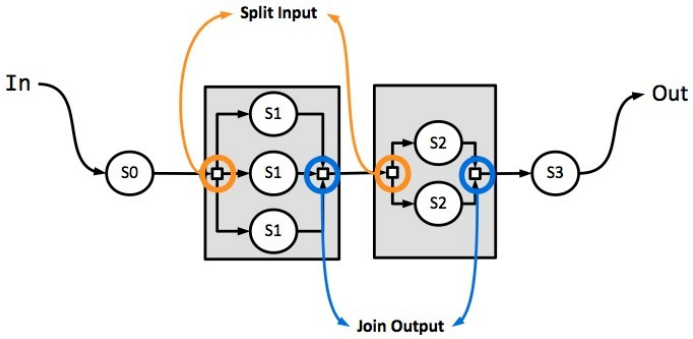
2. if $< p$ tasks exist, all execute
   - optimal with a factor of 2
   - linear speedup for $\frac{T_1}{T_\infty} \geq P$
- Work stealing scheduler
  - First used in CIlk
  - provably: $T_p = \frac{T_1}{P} + O(T_\infty)$
  - empirically: $T_p \approx \frac{T_1}{P} + T_\infty$
  - $\frac{T_1}{T_\infty} >> P \rightarrow$ linear speedup
  - Parallel slackness: granularity (expressed parallelism > machine parallelism)
  - Why should the programmer care? A: guideline for parallel programs
- Example: Sum the elements of a list, using D&C[4]

```
public static long sum_rec(List<Long> Xs){
    int size = Xs.size();
    if (size == 1)
        return Xs.get(0);
    int mid = size / 2;
    long sum1 = sum_rec(Xs.subList(0, mid));
    long sum2 = sum_rec(Xs.subList(mid, size));
    return sum1 + sum2;
}
```

```
Divide and Conquer:
    if cannot divide:
        return unitary solution (stop recursion)
    divide problem in two
    solve first (recursively)
    solve second (recursively)
    combine solutions
    return result
```

- So far: Dynamic task graph, but the graph can also be static, i.e. does not change with time
  - Pipeline
    - Think Laundry as an example
    - In full utilization, output rate is 1 item per time unit
    - Time unit is determined by the slower stage: a slower stage stalls the pipeline
    - Hence, we try to create pipelines where each stage takes (roughly) the same amount of time
    - Achieved using splits and joins for parallel stages

[4] D&C: Divide and Conquer

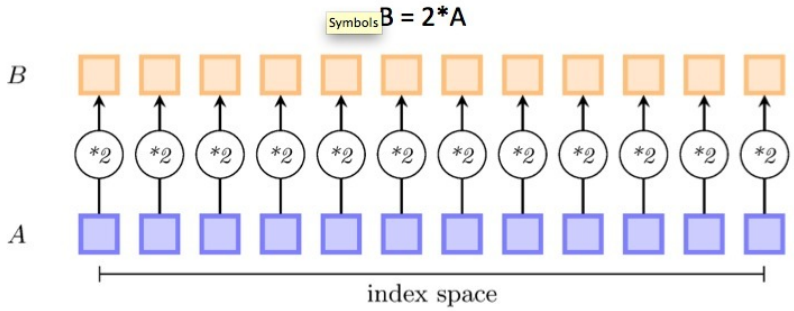


  * Streaming

    There isn't a single thing in the slides about streaming

  * Dataflows
    - Programmer defines: what each task does, and how the tasks are connected
    - Scheduling: Assigning nodes (tasks) into processors
    - $n < p$: cannot utilize all processors
    - $n == p$: one node per processor
    - $n > p$: need to combine tasks; portability, flexibility (parallel slackness); balancing, minimize communication (graph partitioning)
    - Dataflow programming is a good match for parallel programming since the programmer is not concerned with low-level details; and the same program is used for different platforms (e.g. shared/distributed memory → different edge impl.)

- Data parallel: An operation is applied simultaneously to an aggregate of individual items (e.g. arrays) (productive, not general)
  - In task parallelism, programmer describes what each task does and the task graph (dynamic or static)
  - In data parallelism, the programmer describes an operation on an aggregate of data items.
    * Data partitioning is done by the system
    * D.P. is declarative: programmer describes what, not how
  - Example: Map



        * Each operation can be performed in parallel
        * Work partitioning → partition the index space
    - Reductions
        * Simple examples: sum, max
        * Reductions over programmer-defined operations
            · Operation properties (associativity/commutativity) define the correct executions
            · Supported in most parallel languages/frameworks
            · powerful construct
        * Other data types than arrays
        * similar operation: prefix scan
    - Parallel Loops
        * So far: work partition → partition object (e.g. array) index space
        * Iterations can (but do not have to) perform in parallel: work partitioning → partition iteration space
        * Add generality
        * Potential source of bugs if thought of as a sequential loop due to data races

- Managing State: Main challenge for parallel programs. There are different approaches:
    - Immutability
        * Data does not change
        * best option, should be used when possible
    - Isolated mutability
        * Data can change, but only one execution context can access them
        * message passing for coordination
        * State is not shared
        * Each task (actor) holds its own state
        * (Asynchronous) messages
        * Models:
            · Actors
            · Communicating Sequential processes (CSP)
    - Mutable/shared data
        * Data can change/all execution contexts can potentially access them
        * Enabled in shared memory architectures
            · **However**: concurrent accesses may lead to inconsistencies
            · **Solution**: protect state by allowing only one execution context to access it at a time
        * State needs to be protected
            · Exclusive access

        - intermediate inconsistent states should not be observed[5]
    - Methods
        - **Locks**: Mechanisms to ensure exclusive access/atomicity; ensuring good performance/correctness with locks can be hard
        - **Transactional Memory**: Programmer describes a set of actions that need to be atomic; easier for the programmer, but getting good performance might be challenging

5 Introduction to (Parallel) Programming

Not really needed??

6 Introduction to Java

Only the technical things are discussed, no basic java syntax!

- Java is an interpreted language
    - Platform independence via bytecode interpretation
    - Java programs run (in theory) on any computing device (PC, mobile, linux, etc.)
    - Java compiler translates source to byte code
    - Java Virtual Machine (JVM) interprets compiled program
- Compiling/Running
    1. Write it
        - Code or source code: The set of instructions in a program
    2. Compile it
        - Compile: Translate a program from one language to another
        - Byte code: The java compiler converts your code into a format named *byte code* that runs on many computer types
    3. Run (execute) it
        - Output: The messages printed to the user by a program
- JVM Bytecode interpretation
    - JVM interprets compiled Bytecode
    - Simulates a virtual CPU (or rather an entire machine)
    - Translates bytecode into architecture dependent machine code at runtime
    - Loss in performance due to interpretation?

[5] Think two people at the blackboard example

    - Yes and no
    - Some overhead due to interpretation step but JVM is highly optimized
    - Other language constructs impact performance more

- Structure of a Java program

```
public class name {
        public static void main(String[] args){
                statement;
                statement;
                ...
                statement;
        }
}
```

  Where:

  - **class**: a program
  - **method** (`main`): a named group of statements
  - **statement**: a command to be executed

  Also:

  - `import` statement makes classes and methods from other packages (API) available
  - The **class body** contains:
    - Instance and class variables (attributes)
    - Names constants
    - Class specific methods (**static** methods)
  - **Methods** are what we called functions or procedures so far
    - **Constructor** is a special method that gets called automatically on object creation
  - **Methods** must have a name and optionally have:
    - List of parameters
    - Local variables
    - Instructions (statements)
  - Each **class** can be compiled independently

```
import ...

class A {
        class body

        constructor {
            ...
        }
        method_m1 {
            ...
```

```
        }
        method_m2 {
            ...
        }
}

class B {
    ...
}
```

- In Java, the main method is called at runtime automatically, it serves as the entry point. Methods are then called from here.

7 Loops/Objects/Classes

- The `for` loop
  - The for loop statement performs a task many times
  - syntax:

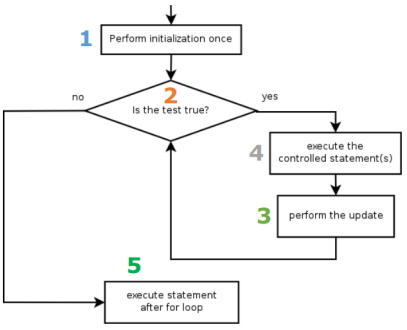
```
for (initialization;test;update){
  statement;
  statement;
    ...
  statement;
}
```

  - It performs initialization once
  - Repeat the following:
    - Check if the test is true. If not, stop.
    - Execute the statements.
    - Perform the update
- Loop walkthrough

```
for (int i=1; i<=4; i++){
    System.out.println(i + " squared = " + (i*i));
  }
  System.out.println("Whoo!");
```

Output:
1 squared = 1
2 squared = 4
3 squared = 9

4 squared = 16



Whoo!

- Categories of loops
  - **Definite loop**: Executes a known number of times.
    - The `for` loops we have seen are definite loops
      - Print "Hello" 10 times.
      - Find all the prime numbers up to an integer n.
      - Print each odd number between 5 and 127
  - **Indefinite loop**: One where the number of times its body repeats is not known in advance.
    - Prompt the user until they type a non-negative number.
    - Print random numbers until a prime number is printed.
    - Repeat until the user has types "q" to quit.
- The `while` loop:
  - It repeatedly executes its body as long as a logical test is true.
  - Syntax:

```
while (test){
    statement;
}
```

  - `while` is better than `for` because we don't know how many times we will need to increment to find the factor.
- Sentinel values:
  - **Sentinel loop**: it repeats until a sentinel value is seen
  - Sentinel code example:

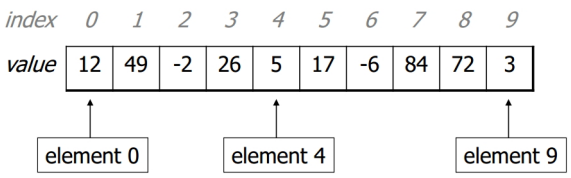
```
Scanned console = new Scanner(System.in);
int sum = 0
//pull one prompt/read out of the loop
System.out.print(``Enter a number (-1 to quit): '');
int number = console.nextInt();

while (number != -1){
  sum=sum+number;  //moved to top of loop in order to avoid
                   //fencepost problems
```

```
  System.out.print(``Enter a number (-1 to quit): '');
  number = console.nextInt();
}

System.out.println(``The total is '' + sum);
```

- The `do/while` loop
  - It performs its test at the end of each repetition.
    - It guarantees that the loop's body will run at least once.
    - Syntax:

```
do{
  statement;
} while (test);
```

- Arrays
  - **Array**: object that stores many values of the same type.
    - **element**: One value in an array.
    - **index**: A 0-based integer to access an element from an array



  - Accessing elements

```
name[index]          //access
name[index] = value; //modify
```

  - One can use `for` **loops** to insert elements in the array
  - Arrays are reference types
  - Out-of-bounds exception
    - Legal indexes: between **0** and the **array's length -1**.
      - Reading or writing any index outisde this range will throw an `ArrayIndexOutOfBoundsException`

- Strings
  - **String**: An object storing a sequence of text characters
    - Unlike most other objects, a `String` is not create with `new`.
    - Syntax:

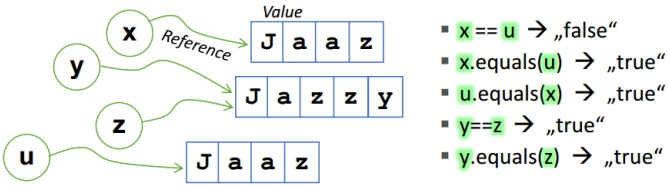
```
String name = ‘‘text’’;
String name = expression;
```

- Indexes
  - Characters of a string are numbered with 0-based *indexes*:
    - First character's index: 0
    - Last character's index: 1 less than the string's length
    - The individual characters are values of type chars
- String methods

Method name	Description
`indexOf(`**str**`)`	index where the start of the given string appears in this string (-1 if not found)
`length()`	number of characters in this string
`substring(`**index1**`, `**index2**`)` or `substring(`**index1**`)`	the characters in this string from *index1* (inclusive) to *index2* (exclusive); if *index2* is omitted, grabs till end of string
`toLowerCase()`	a new string with all lowercase letters
`toUpperCase()`	a new string with all uppercase letters

This methods are called using the dot notation

- Comparing strings
  - "==" compares objects by *references*, so it often gives `false` even when two `Strings` have the same letters
  - Example:



- String test methods

Method	Description
`equals(`**str**`)`	whether two strings contain the same characters
`equalsIgnoreCase(`**str**`)`	whether two strings contain the same characters, ignoring upper vs. lower case
`startsWith(`**str**`)`	whether one contains other's characters at start
`endsWith(`**str**`)`	whether one contains other's characters at end
`contains(`**str**`)`	whether the given string is found within this one

```
String name = console.next ();
  if (name.startsWith(``Prof''')){
      System.out.println(``When are your office hours?'');
  } else if (name.equalsIgnoreCase(``STUART'')){
      System.out.println(``Lets talk about meta!``);
  }
```

- Extracted from Java API
  - `compareTo`
    - `public int compareTo(String anotherString)`
      Compares two strings lexicographically
    - **Parameters**:
      `anotherString` - the String to be compared
    - **Returns**:
      The value 0 if the argument strings is equal to this string, less tha 0 if it is lexicographically less than the string argument, value greater than 0 otherwise
  - `concat`
    - `public String concat(String str)`
      Concatenates the string argument to the end of this string.
    - **Parameters**;
      `str` - the String which is concatenated to the end of this String
    - **Returns**: A string that represents the concatenation of this object's characters followed by the string argument's characters
  - `copyValueOf`
    - `public static String copyValueOf(char data[])`
    - **Parameters**:
      `data` - the character array
    - **Returns**:
      A string that contains the characters of the array
- Classes and objects
  - **Class**:
    - A program entity that represents either:
      1. A program/module, or
      2. A type of objects
    - A class is a blueprint or template for constructing objects
- **Object**: An entity that combines data and behavior.
  - **object-oriented programming (OOP)**:
    Programs that perform their behavior as interactions between objects.
    - data: variables inside the object
    - behavior: methods inside the object

        - You interact with the methods; the data is hidden in the object
    - Constructing an object:
      `Type objectName = new Type (parameters);`
    - Calling an object's method:
      `objectName.methodName (parameters);`

- Inheritance
  Even though there are systematic differences, different kinds of objects often have a certain amount in common with each other.
  Classes *inherit* commonly used state and behaviour from other classes, but specialized behaviour and states further

WTF??

- References and objects
  - Arrays and objects use reference semantics, because of:
    - *efficiency*: Copying large objects slows down a program
    - *sharing*: It's useful to share an object's data among methods
    - Example:

```
DrawingPanel1 panel1 = new DrawingPanel (80, 50);
DrawingPanel panel2 = panel1; //same window
panel2.setBackground(Color.CYAN);
```

- Objects as parameters
  - When an object is passed as a parameter, the object is *not* copied. The parameter refers to the same object.
    - If the parameter is modified, it *will* affect the original object.

```
public static void main(String[] args) {
        DrawingPanel window = new DrawingPanel(80, 50);
        window.setBackground(Color.YELLOW);
        example(window);
}

public static void example(DrawingPanel panel) {
        panel.setBackground(Color.CYAN);
        ..
}
```

- Arrays pass by reference
  - Arrays are passed as parameters by *reference*.
    - Changes made in the method are also seen by the caller

```
public static void main(String[] args) {
        int[] iq = {126, 167, 95};
        increase(iq);
        System.out.println(Arrays.toString(iq));
}
```

```
public static void increase(int[] a) {
        for (int i = 0; i < a.length; i++) {
                a[i] = a[i] * 2;
        }
}

Output:
[252, 334, 190]
```

- Arrays of objects
  - `null`: A value that does not refer to any object.
    - The elements of an arays of objects are initialized to `null`.

- Things you can do with null:
  - store `null` in a variable or an array element
  - print a `null` reference
  - ask whether a variable or array element is `null`
  - pass `null` as a parameter to a method
  - return `null` from a method (often to indicate failure)
- Null pointer exception
  - *dereference*: To access data or methods of an object with the dot notation, such as `s.length()`.
    - It is illegal to dereference `null` (causes an exception)
    - `null` is not any object, so it has no methods or data.
  - One can avoid raising an exception by simply using a if case statement before calling an object's method:

```
if (words[i] != null){
        ...
}
```

- Encapsulation
  - Encapsulation is a very important O-O concept
    - Each object has 2 views. An internal view and an external view
  - Encapsulation is a form of protection
    - Also called *Information Hiding*
    - The outside world does not have direct access to the internal implementation or representation of an object
    - As long as the external view does not change, the internal view can take on any form without affecting the outside world
    - Methods have the responsibility of maintaining data integritiy
  - Private visibility offer full encapsulation

    - protected and default offer limited encapsulation
    - public offers no encapsulation
  - Benefits
    - Abstraction between object and clients
    - Protects object from unwanted access
      - Example: One can't fraudulently increase an `Account`'s balance
    - Can change the class implementation later
      - Example: `Point` could be rewritten in polar coordinates with the same methods,
    - Can constrain object's state (**invariants**)
      - Example: Only allow `Accounts` with non-negative balance.
      - Example: Only allow `Dates` with a month 1-12-

  Un po' ripetitivo...???

- Java access restrictions
  - **Packages**: define a name space
  - Default package used in the absence of a package declaration
  - For class members you can specify which other objects can access (read/write or invoke) them
    - (default)[nothing]: accessible in current package
    - `public`: everywhere
    - `private`: only from this class
    - `protected`: accessible in current package and all subclasses, regardless of their package

- Private fields
  - A field that cannot be accessed from outside the classe
    `private type name;`

- The `this` keyword
  - `this`: Refers to the implicit parameter inside your class.
    (a variable that stores the object a method is called)
    - Refer to a field `this.field`
    - Call a method: `this.method(parameters);`
    - One constructor can call another: `this(parameters);`

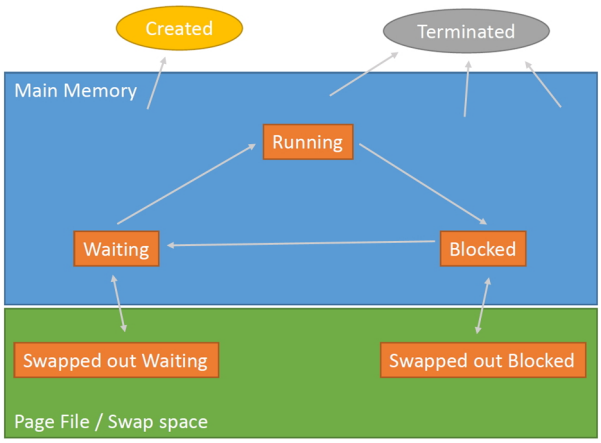
- Class versus Instance Methods
  - **Class methods** are marked by the `static` keyword.
    - They are not called via an object reference but directly via the class
    - Can be called from a static context.
    - often serve as utility function.

* They are generic and need no access to object variables and methods

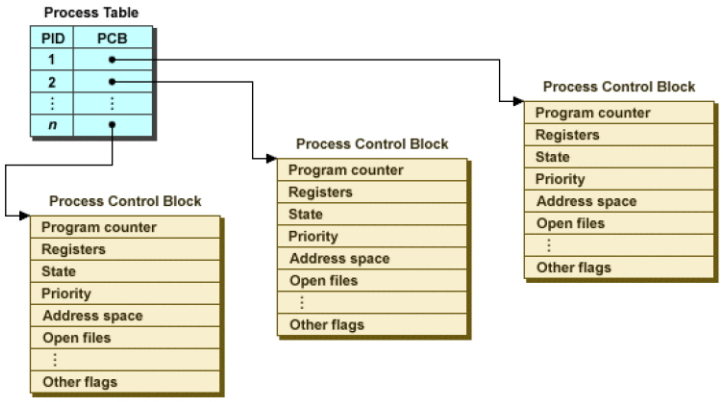
```
classDatum {
       privateintday, month, year;
       staticString monthName(Datum d)
              {
                     if(d.month== 1) return "January";
                     if...                  return
                          "February";
                     ...
              }
       ...
}
```

8 Threads

- Multitasking
  - Concurrent execution of multiple tasks
  - Time multiplexing of CPU
    * Creates impression of parallelism, even on single core/CPU system
  - Allows for asynchronous I/O
    * I/O devices and CPU are truly parallel
    * 10ms waitinf for HDD allows other processes to execute $> 10^{10}$ instructions
- Process context
  - Multiple concurrent instances of **same program** (e.g., multiple browser windows)
  - Multiple applications (=processes) in parallel
  - Each process has a **context**
    * Instruction counter
    * Register content
    * Variable values
    * Stack content
    * Resourcing (device access, open files)
- Process States



- Process management
  - Processes need resources
    - CPU time, Memory, etc.
  - OS manages processes:
    - Starts processes
    - Terminates processes (frees resources)
    - Controls resource usage (prevents monopolizing CPU time)
    - Schedules CPU time
    - Synchronizes processes if necessary
    - Allows for inter process communication
- Process control blocks (PCB)



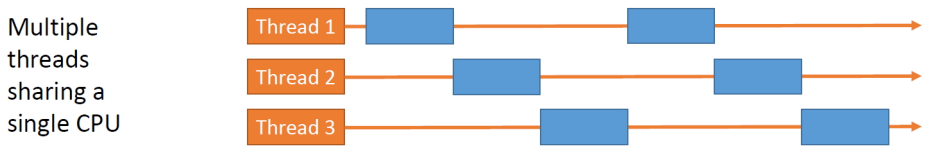
Java Threads

- Threads (light weight processes)
  - **Threads** (of control) are independent sequences of execution, but multiple threads **share the same address space**

    - Threads are not shielded from each other
    - Threads share resources and can communicate more easily
  - Context switching between threads is much more efficient for threads
    - No change of address space
    - No automatic scheduling
    - No saving / (re-)loading of PCB state
  - Many more thread changes possible than process switches per unit of time

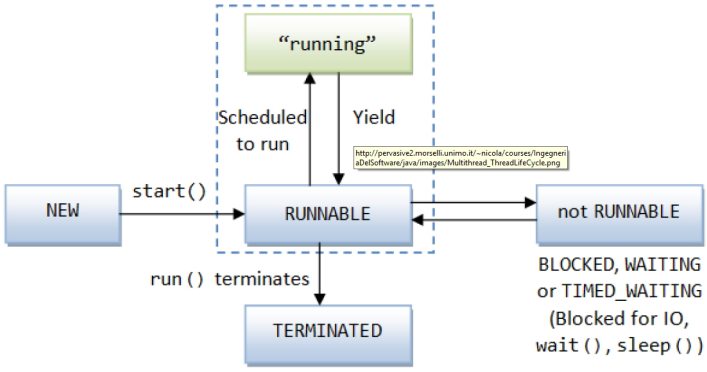
- Advantages of Multithreading
  - Reactive systems: constantly monitoring
  - More responsive to user input: GUI application can interrupt a time-consuming task
  - Server can handle multiple clients simultaneously
  - Can take advantage of parallel processing

- Multithreading conceptually



- Two options to create Java Threads
  - Extend `java.lang.Thread` class
    - Override run method (must be overridden)
    - `run()` is called when execution of the thread begins
    - A thread terminates when `run()` returns
    - `start()` method invokes `run()`
    - Calling `run()` does not create a new thread
  - Implement `java.lang.Runnable` thread
    - If already inheriting another class (i.e., JApplet)
    - Single method: `public void run()`
    - Thread class implements Runnable

- Thread state model in Java



- Important to know
  - Every Java program has at least one execution thread
    - First execution thread calls `main()`
  - Each call to `start()` method of a `Thread` object creates new thread
  - Program ends when all threads (non-daemon threads) finish
  - Threads can continue to run even if `main()` returns
  - Creating a `Thread` object doesn't start a thread
  - Calling `run()` doesn't start thread either
- Getting and setting Thread info
- `Thread` class provides attributes that can help us identify a thread
  - **ID**: This attribute stores a unique identifier for each Thread.
  - **Name**: This attribute store the name of Thread.
  - **Priority**: This attribute stores the priority of the Thread objects. Threads can have priority between 1 and 10
  - **Status**: one of these six states:
    - new, runnable, blocked, waiting, time waiting or terminated
- Controlling Thread interrupts
  - `Thread.interrupt()` requests a thread interruption
  - Can be ignored if the thread chooses so
  - Can be handled with fine grain control
    - `isInterrupted()`
    - `interrupted()`
- Threads and Exceptions
  - **Checked** Exceptions:
    - represent invalid conditions in areas outside the immediate control of the program (network outages, absent files)
    - are subclasses of Exception

    - a method is obliged to establish a policy for all checked exceptions thrown by its implementation (either pass the checked exception further up the stack, or handle)
  - **Unchecked** Exceptions:
    - represent conditions that reflect errors in your programs logic and cannot be recovered from at run time (bugs)
    - subclasses of RuntimeException, and are usually implemented using `IllegalArgumentException`, `NullPointerException`, or `IllegalStateException`
    - a method is not obliged to establish a policy for the unchecked exceptions thrown by its implementation

- Setting `UncaughtExceptionHandlers`
  Implementing `UncaughtExceptionHandler` interface allows us to handle unchecked exceptions
  Three options:
  - Register exception handler with Thread object
  - Register exception handler with ThreadGroup object
  - Use `setDefaultUncaughtExceptionHandler()` to register handler for all threads

9 Synchronization

Introduction to Locks

- Synchronization is needed in order to avoid race conditions
- Shared state must be protected because they are accessed by threads- Access includes both reads and writes!
  - Concurrent access might lead to inconsistencies
    - Concurrent access bugs often depend on execution conditions
  - Using sequential algorithms on shared data is unsafe; they typically assume that they act alone
  - hardware/software optimizations for sequential computations; assume sequential execution
- Race conditions and data races
  - race condition: The correctness of a computation depends on relative timing
  - data race: unsynchronized access to shared mutable data
  - Closely related concepts: most race conditions are due to data races
  - but not al race conditions are data races and not all data races are race conditions!
- To avoid race conditions use synchronized threads via atomic mutual exclusion

- Atomic operation
  - Operations **A** and **B** are atomic with respect to each other if:
    - Thread 0 executes A
    - Thread 1 executes B
    - Thread 0 always perceives either all of B or none of it (nothing in between)
  - An operation is atomic if is atomic with respect to all operations on the same state
- Thread safety
  In order to achieve multi-threaded correctness of the whole program, one should:
  - Apply OO techniques (encapsulation)
    - Design "thread safe classes"
      - they encapsulate any needed synchronization so that the clients do not need to provide their own
    - Build your program by composing thread-safe classes

  A Thread safe class:
  - Behaves correctly when accessed by multiple threads
    - Data-race free
  - Does not require synchronization from users
- Synchronization is not easy
  - Concurrent access breaks many assumptions from sequential programming. Therefore NO assumptions can be made about the relative execution speed of threads
  - Synchronizing with `Sleep()` is wrong
- Locks
  - A lock object instance defines a critical section
  - lock → enter critical section
  - unlock → leave critical section

```
mylock.lock();
// critical section
...
//critical section ends
mylock.unlock();
```

- Java intrinsic locks
  - Each java object contains a lock (java built-in mechanism)
  - These locks can be used via the `synchronized` keyword

```
synchronized (obj){
      //critical Section
}
```

- Reentrant locks

```
class Reentrant {
       public synchronized void
       fn1() {...}

       public synchronized void
       fn2() {
              ... fn1(); ...
       }
}
```

  - Entering `fn2` acquires the lock
  - `fn2` calls `f1` → entering `f1` also acquire lock
  - With normal locks this causes a deadlock:
    - A situation where the program is unable to proceed
  - Reentrant locks: if a thread tries to acquire a lock it already holds it succeeds

- Reentrant vs non-reentrant locks
  - reentrant locks → per thread acquisition
    - requires a counter
  - non-reentrant locks → per-invocation acquisition
    - not a good match for intrinsic locks
  - trade-off: flexibility ↔ productivity

- Atomic counter

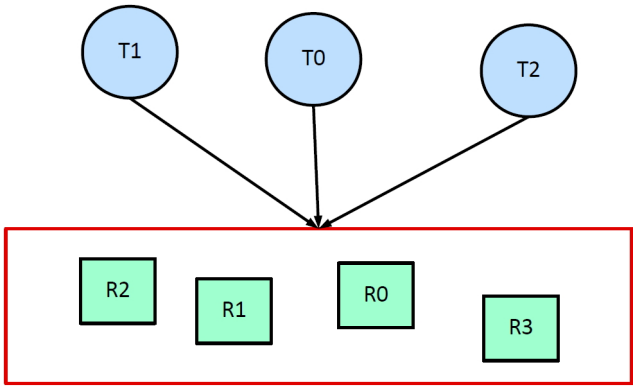
```
class AtomicCnt{
       private long value;

       synchronized long get(){
              return value;
       }

       synchronized void inc(){
              value++;
       }
}
```

- Caching results
  - cache: input → result

    - A mapping of a set of input elements to the corresponding results of a computation
  - Is result in cache?
    - Yes: return result
    - No: do computation, store result in cache and then return result

Using locks and building thread-safe classes

- Coarse-grained locking



  Performances:

  - Locks are serialization points
  - big locks → large sequential regions
  - can significantly hurt parallel performance (Amdahl's law)
  - good parallel performance requires avoiding big critical regions

- Deadlocks
  - Fine-grained locking introduces the possibility of a deadlock
  - A deadlock happens when a number of threads reach a point where they are unable to continue
    - caused by circular dependencies
    - it is a run-time condition

- Necessary conditions for a deadlock to occur
  - Mutual exclusion
    at least one resource must be non-shareable
  - Hold an wait
    a thread holds at least a lock that it has already acquired, while waiting for another lock
  - No forced lock release
    locks can only be released voluntarily by the threads

  - Circular wait:
    p_1 waits for p_2
    p_2 waits for p_3
    ...
    p_x waits for p_1

- Circular wait condition
  To break the circular wait condition and avoid a deadlock to occur:
  - Set a global order of locks
  - Acquire locks respecting that order
  - Impossible to create a condition of circular wait
  - impossible to deadlock!

- Building thread-safe classes
  - Mutable and shared data need to be protected
  - Immutable is always thread safe after initialization
  - stateless is always thread safe

    Try to avoid synchronization when possible; it is difficult to reason about it, and there are some performance issues

- The Java `final` keyword
  - A final **class** cannot be subclassed
  - A final **method** cannot be overridden or hidden by subclasses
  - A final **variable** can only be initialized once

- Java Immutable Objects
  An object is `immutable` if:
  - Its state cannot be modified after construction
  - All its fields are final
  - It is properly constructed (while the constructor runs, the object is mutable, there fore it should not be accessed during that time)

- `AtomicReference<V>`
  - Atomic access to a reference of V
  - Operations:
    * get
    * set, lazySet
  - `.get()` and `.set()` $\leftrightarrow$ same semantics with `volatile`
    * We use `AtomicReference` because it is more explicit
    * Avoid confusion with `volatile` from other language

- Immutable vs. non-Immutable objects
  - Immutable objects are **special**

    - This is specified by the Java memory model
    - They do not require safe publication
  - Non-Immutable objects need to be **safely published**
    - no ordering guarantees provided by the memory model
    - A thread might observe a non-safely published object in an inconsistent state

- Encapsulation
  - hide information for users of a class
  - general OO technique
  - applies to synchronization in parallel programming
  - class hides internal state (fields,...)
  - provides methods for accessing objects
  - users of the class cannot directly access state

- Delegation
  - Use existing thread-safe classes to build our class
    - The resulting class is not always thread-safe!
  - Delegation is not always possible
    - multiple state variables
    - can be delegated safely if:
      - state variables are thread-safe
      - state variables are independent
      - not valid state transitions
    - Additional synchronization is usually needed
      Counter-example

```
public class NumberRange {
        // INVARIANT: lower <= upper
        private final AtomicInteger lower = new
            AtomicInteger(0);
        private final AtomicInteger upper = new
            AtomicInteger(0);
        public void setLower(int i) {
                // Warning -- unsafe check-then-act
                if (i > upper.get())
                        throw new
                            IllegalArgumentException(...)
                lower.set(i);
        }

        public void setUpper(int i) {
        // Warning -- unsafe check-then-act
        if (i < lower.get())
                throw new IllegalArgumentException(...);
        upper.set(i);
}
```

10 Synchronization: Beyond Locks

- Locks provide means to enforce atomicity via mutual exclusion
- They lack means for threads to communicate about changes, e.g. changes in state
- Example: producer/consumer (p/c) queues (think: bakery)
  - can be used for data-flow parallel programs, e.g. pipelines where a mean to transfer X from the producer to the consumer is needed
  - There might be multiple producers or (not xor) multiple consumers
  - For an implementation a circular buffer (with a fixed size) can be used with simple `dequeue()`/`enqueue()` and an in and out counter. Both functions use a shared (reentrant) lock and rely on helper functions to check for full/empty queue[6]
  - If you use a busy wait (while loop) there is a chance of a deadlock (and CPU running high). Using sleep for synchronization as another approach is generally discouraged
  - The solution is a condition variable which (ideally) notifies the threads upon change
- A condition interface provides the following methods:
  - `await()`: the current thread waits until it is signalled.
    - Called with the lock held
    - Releases the lock atomically and waits for thread to be signalled
    - When returns, it is guaranteed to hold the lock
    - Thread always needs to check condition
  - `signal()`: wakes up one waiting thread. Called with the lock held
  - `signalAll()`: wakes up all waiting threads. Is called with the lock held

Conditions are always associated with a lock

- Check then act!
- Conditions can also be used with intrinsic locks where each object can act as a condition, implementing `.notify()`, `.notifyAll()`, `.wait()`.
  - They do not allow for multiple conditions (e.g. different condition for Full/Empty in P/C queues)
- `Object.wait` and `Condition.await`:
  - always have a condition predicate
  - always test the condition predicate: before calling wait and after returning from wait

[6]Note: If you have a try-catch-finally block and there is a return statement (assume it will be called no matter what) in the "try" part and an unlock() in the "finally" part, the finally part will always be executed (and thus also the lock released!).

  - always call wait in a loop
  - Ensure state is protected by lock associated with condition

- Semaphores[7]
  - Invented by Dijkstra
  - Operations:
    * **Initialize** to an integer value
      · After initialization only wait/signal operations are allowed
    * **Acquire**:
      · Integer value is decreased by one
      · If $< 0 \rightarrow$ thread suspends execution
    * **release**
      · Integer value is decreased by one
      · If there is at least a thread waiting, one of the waiting threads resumes execution
  - Notes on Semaphores:
    * A thread cannot know the value of a semaphore, and thus cannot know whether its execution will be suspended if it calls `acquire()`
    * There is no rule about what thread will continue its operation after `release()`
    * Operations are traditionally also referred to as
      · *P()*: acquire (also wait)
      · *V()*: release (also signal)
  - Building a lock with a semaphore:
    * mutex[8] = Semaphore(1); Initialize mutex using a semaphore, and set it to unlocked (1)
    * lock mutex $\rightarrow$ `mutex.acquire()`; only one thread is allowed into the critical section
    * unlock mutex $\rightarrow$ `mutex.release()`; One other thread will be woken up
    * Semaphore number:
      · 1 = unlocked
      · 0 = locked
      · $-x$ = locked and x threads are waiting to enter
  - You can (of course) also use semaphore for p/c queues, however you need to use two semaphores to order the operations (and to prevent a deadlock).

- Barriers
  - Rendezvous for arbitrary number of threads i.e. every thread has to wait up for all other threads to arrive at a certain point

[7] Language background: semaphore is fancy for traffic light in English (see also Spanish).
[8] Mutual Exclusion Locks: make sure that at most one thread owns the lock

- Can be implemented for n threads with:
  - two semaphores (and one count variable):
    - One as a mutex (used to atomically increment the counter) with default = 1
    - One as a barrier with default = 0 (which is released if count == n and otherwise only acts as acquire-and-release-immediately).

```
count = 0
mutex = Semaphore(1)
barrier = Semaphore(0)

mutex.acquire()
   count = count + 1
mutex.release()

if (count == N){
   barrier.release()
}

barrier.acquire()
barrier.release()
```

- If you want a reusable barrier for n threads (aka 2-phase barrier) with semaphores, you need a count, a mutex and two barriers for it to be thread-safe.

```
count=0; mutex = Semaphore(1); bar0 = Semaphore(0); bar1 =
    Semaphore(1);

mutex.acquire()
count +=1
if (count == N){
  bar1.acquire()
  bar0.release()
}
mutex.release()

bar0.acquire()
bar0.release()

mutex.acquire()
count -= 1
if (count == 0){
  bar0.acquire()
  bar1.release()
}
mutex.release()

bar1.acquire()
bar1.release()
```

11 Advanced (and other) Topics

- Locks can be implemented with low-level atomic operations (basic operations that are guaranteed to be atomic) and busy wait loops (a thread continuously checks a condition)
  - Example: Peterson Lock

```
AtomicBoolean t0 = new AtomicBoolean(false);
AtomicBoolean t1 = new AtomicBoolean(false);
AtomicInteger victim = new AtomicInteger(0);
lock:
    my_t.set(true)
    victim.set(me);
    while (other_t.get() == true &&victim.get() == me)
        ;

        unlock:
        my_t.set(false);
```

    Two `AtomicBooleans` (one per thread) and an `AtomicInteger` which decides which thread will be selected. This only works for two threads. The entities `my_t`, `other_t` and `me` depends on the thread: for thread0 `my_t=t0, other_t=t1, me=0` and for thread1 is the opposite.

- In order to make our life easier, we need rich(er) atomic operations for AtomicInteger:
  - `getAndSet(val)` (atomically set to val, return old value)
  - `getAndAdd(val)`
  - `getAndIncrement`
  - `getAndDecrement`
  - `CompareAndSet` (CAS for short)
- Lock using `getAndSet`: mutex is an AtomicBoolean which is set to either true or false on lock or unlock (resp.)

```
mutex = new AtomicBoolean(false);
lock:
  while (mutex.getAndSet(true));
unlock:
  mutex.set(false);
```

- CAS; performs atomically the following (optimistically):

```
atomic_int.compareAndSet(int old, int new)

atomically {
  if (current_val == old) {
    current_val=new
    return true
  }
```

```
  else {
     return false
  }
}
```

- Lock using `getAndSet`:

```
mutex = new AtomicBoolean(false);

lock:
  while (mutex.getAndSet(true));

unlock:
  mutex.set(false);
```

- Busy-wait
  - Check continuously for a value
  - Wastes CPU-time
  - Alternative: exponential backoff
  - Ideally we would like some sort of notification mechanism
- Mutexes:
  - Locks that suspend the execution of threads while they wait are typically called mutexes (vs spinlocks)
  - Scheduler (typically from the OS) support is required
  - They do not waste CPU time but they have higher wakeup latency
  - Hybrid approach: spin and then sleep
- Locks performance:
  - Uncontended case:
    - When threads do not compete for the lock
    - Lock implementations try to have minimal overhead, typically just the cost of an atomic operation
  - Contended case:
    - When threads do compete for the lock
    - Can lead to significant performance degradation, as well as starvation
- Disadvantages of locking
  - locks are pessimistic by design, they assume the worse/worst and enforce mutual exclusion
  - Performance issues:
    - Overhead for each lock taken even in uncontended case
    - Contended case leads to significant performance degradation

  - blocking semantics (wait until acquire lock)
    * if a thread is delayed for a reason (e.g., scheduler) when in a critical section → all threads suffer
    * Leads to deadlocks (and also livelocks)

- Non-blocking algorithms:
  - Locks: a thread can indefinitely delay another thread
  - Non-blocking: failure or suspension of one thread cannot cause failure or suspension of another thread
  - Lock-free: at each step, some thread can make progress
  - Typically built using CAS operations(more powerful than plain-atomic)
    * see lecture slides for stack example (Page 18)
    * Non-blocking counter example:

```
public class CasCounter {
  private AtomicInteger value;

  public int getVal() {
    return value.get();
  }

  public int inc() {
    int v;
    do {
       v = value.get();
    } while (!value.compareAndSet(v, v+1));
    return v+1;
  }
}
```

11.1 An overview of java.util.concurrent

- Lock interface:

```
void lock()
void lockInterruptibly()

boolean tryLock()
boolean tryLock(long time, TimeUnit unit)

void unlock()
Condition newCondition()
```

  Interface implemented by ReentrantLock

- Readers-Writer Lock
  - Observation: multiple readers can concurrently access state
  - Different roles:

    - Readers: Allow to co-exist with other readers
    - Writers: Exclusive access
  - Beneficial for "read-mostly" workloads
  - Can be implemented with semaphores but fairness might be an issue leading to starvation[9] unless prevented by means to notify the read lock about waiting writers

- Java collections
  - Aggregate Objects: Objects that group multiple elements into a single unit
  - Interfaces (e.g. `Collection, List, Set, SortedSet`,...)
  - Implementations (e.g. `ArrayList` and `LinkedList` for `List`)
  - Algorithms (e.g. `Sort`)

  → Based on Java Generics

- Synchronized Collections:
  - Vector, HashTable (JDK 1.0)
  - java.util.collections (JDK 1.2):
    - `synchronizedList(List<T> list)`
    - `synchronizedMap(Map<K,V> m)`
    - `synchronizedSet(Set<T> s)`
    - `synchronizedSortedMap(SortedMap<K,V> m)`
    - `synchronizedCollection(Collection<T> c)`
  - They are synchronized wrapper classes
  - Wrap every public method in a synchronized block
  - Thread-safe
  - Client-side locking for compound actions (e.g. iteration, put-if-absent)
  - Poor concurrency: single, collection-wide lock

- Concurrent Collections:
  - Thread-safe
  - Not governed by a single lock
    - Cannot be locked for exclusive access
    - No client-side locking
    - Common compound operations added (e.g. put-if-absent, replace-if-equal,...)
  - Examples:
    - `ConcurrentHashMap`
      - As a replacement for synchronized hash-based map

[9] Starvation: when a particular thread cannot resume execution; different from deadlock, where all the threads are unable to proceed

        * `ConcurrentSkipListMap`, `ConcurrentSkipListSet`
            · As a replacement for synchronized tree-based impls.
        * `CopyOnWriteArrayList`, `CopyOnWriteArrayList`
            · Frequent reads, infrequent writes

- Queues:
    - `BlockingQueue`
        * `ArrayBlockingQueue`, `LinkedBlockingQueue` (FIFO)
        * `PriorityBlockingQueue` (ordered)
    - `TransferQueue`: allows to wait until a consumer receives item;
    - `SynchronousQueue`: hand-of, no internal capacity
    - `Dequeue`/`BlockingDeque`:
        * Allows efficient removal/insertion at both ends (head/tail)
        * Work stealing pattern
- Synchronizers:
    - Semaphores
    - `CyclicBarrier` (Java's barrier)
    - `CountDownLatch` (thread wait until countdown reaches zero)
        * `CountDownLatch(int count)` - initialize latch
        * `.await()` - wait for event
        * `.countDown()` - decrement count
- Future: `interface Future<V>`
    - Represents a result (type `T`) for an asynchronous computation
    - `.get()` - wait for result
    - `.isDone()` - check if task is completed
    - `.cancel()` - attempt to cancel computation

12 Parallel Tasks

Example for most of this section: $\sum x_i$

```
public static int sum(int[] xs) {
        int sum = 0;
        for (int x: xs)
                sum += x;
        return sum;
}
```

- When writing a parallel program, write a sequential version first! This is useful for knowing the results are correct and evaluate the performance of the parallel program

- Divide-and-conquer approach: recursive sum with the lower and upper half of the remaining part which cuts off at size = 1 is a lot slower ($\times 10$).
- Task parallel model, basic operations:
  - create a parallel task and wait for the parallel tasks to complete
  - when using D&C a task for the first and second part (one each) are created, and upon finishing the operations, their results are combined
- One thread per task model:
  - expensive to create
  - consumes many resources
  - Scheduled by the OS
  - Generally Inefficient!
- `ExecutorService`: A (huge) amount of tasks is handled by an interface which assigns a thread from a thread pool to each task and returns a Future
- Future (`interface Future<V>`):
  - represents a result (Type `T`) for an asynchronous computation
  - `.get()` - wait for result
  - `.isDone()` - check if task is completed
  - `.cancel()` - attempt to cancel computation
- Note: Callable vs Runnable:
  - Interface Runnable: `void run()`
  - Interface Callable<V>: `V cal()`
  - Runnable doesnt return a result, Callable does
- Executor service for recursive sum[10]:
  - Task is described as
    - The array to be summed
    - The region for which the task is responsible for
  - Additionally, an instance to the `ExecutorService` is passed so that the task can spawn other tasks
  - Problems (observation: no result returned):
    - Tasks create other tasks and then wait for results
    - When they are waiting they are keeping threads busy
    - Other tasks need to run so that the recursion reaches its bottom
    - System does not know that tasks waiting need to be removed so that other tasks can run.
  - Problems with this approach:

[10] Have a look at the code in the slides, pp36-38

    - Tasks create other tasks (which is not supported)
    - Work partitioning (splitting up work) is part of the task
    - We can decouple work partitioning from solving the problem

- Fork/Join framework:
  - `ForkJoinTask<V>`: implements `Future<V>`
  - `ForkJoinPool`: implements `ExecutorService`
  - `.fork()`: creates a new task
  - `.join()`: returns the result when task is done
  - `.invoke()`: executes task without spawning a new task (in-place)
  - subclasses need to define `compute()`

  Note `fork()`, `join()`, `join()` don't work (well) in Java, solved by using[11]

```
t1.fork(), r2 = t2.compute()
return r2 + t1.join()
```

- Problems of overhead:
  - Bad speedup due to too much overhead[12] (scheduling etc.)
  - If the work of each task is small, overheads dominates
    - can be solved by making each task work more, here: increase cutoff

13 Transactional Memory (TM)

- Problems using locks:
  - Ensuring ordering (and correctness) is **really hard**
  - Locks are not composable
  - Locks are pessimistic
  - Locking mechanism is hard-wired to the program
- Aims at removing the burden of having to deal with locks from the programmer and place it on the system instead
- With TM, the programmer explicitly defines atomic code sections and is only concerned with the *what* and not the *how* (declarative approach)
- TM benefits:
  - Easier and less error-prone
  - Higher semantics
  - Composable

[11] "+" is in this case the arithmetic addition but can also be something else of a combining nature

[12] Overheads are time costs that have nothing to do with the computation

  - Optimistic by design

- TM Semantics: Atomicity
  - changes made by a transaction are made visible atomically
  - transactions run in isolation - while a transaction is running, effects from other transactions are not observed (as if transaction takes a snapshot of the global state when it begins and operates on that snapshot)
  - Note: while locks enforce atomicity via mutual exclusion, transactions do not require it.

- TM is inspired by transactions in databases where transactions are vital
  - ACID properties: **A**tomicity, **C**onsistency, **I**solation, **D**urability

- Implementation of TM:
  - Keep track of operations performed by each transaction
  - Big lock around all atomic sections:
    * Gives desired properties, but not scalable
    * Not done in practice for obvious reasons

- Transactions can be aborted if a conflict has been detected by the concurrency control (CC) mechanism
  - aborts are possible e.g. if theres a deadlock
  - on abort, a transaction can be retried automatically or the user is notified

- Where TM is/can be implemented:
  - Hardware TM: can be fast but cannot handle big transactions
  - Software TM (STM): in the language, greater flexibility, performance might be challenging
  - Hybrid TM (Hardware + Software): still work in progress with many different approaches and is still under active development

- Design choice:
  - Strong vs. Weak isolation:

    Q. What happens when shared state accessed by a transaction, is also accessed outside of a transaction? Are the transactional guarantees still maintained?

    A.
    * Strong isolation: Yes,
      · easier for porting existing code
      · difficult to implement, overhead
    * Weak isolation: No
  - Nesting:

Q. What are the semantics of nested transactions? (Note: nested transactions are important for composability)

A.
- Flat Nesting
  - inner aborts → outer aborts
  - inner commits → changes visibly only if outer commits
- Closed nesting: Similar to flattened, but
  - Inner abort does not result in an abort for the outer transaction
  - Inner transaction commits → changes visible to outer transaction, but not to other transaction
  - outer transaction commits → changes of inner transactions become visible
- Other approaches (e.g. open nesting)

- The more variables are part of a transaction (and thus protected) the easier it gets to port existing code but the more difficult to implement (need to check every memory operation)
- Reference-based STMs: mutable state is put into special variables
  - these variables can only be modified inside a transaction, everything else is immutable (or not shared; see functional programming)
- Mechanism of retry:
  - implementations need to track what reads/writes a transaction performed to detect conflicts, typically called read-/write-set of a transaction
  - When retry is called, transaction aborts and will be retried when any of the variables that were read, change
- Issues with transactions:
  - It is not clear what the best semantics for transactions are
  - Getting good performance can be challenging
  - I/O operations: can we perform I/O operations in a transaction?
- I/O in transactions:
  - in general, I/O operations cannot be rolled-back
  - in general, I/O operations cannot be aborted that is why I/O operations are not allowed in transactions
  - one of the big issues with using TM
  - (some) STMs allow registering I/O operations to be performed when the transaction is committed

14 Designing Parallel Algorithms

- There are no rules whatsoever, yet - as (very) often - it is a matter of experience
- The following points can/should be considered:
  - Where do the basic units of computation (tasks) come from?
    - This is sometimes called "partitioning" or "decomposition"
    - Depending on the problem partitioning in terms of input and/or output can make sense or functional decomposition might yield better results
  - How do the tasks interact?
    - We have to consider the dependencies between tasks (dependency, interaction graphs)
    - Dependencies will be expressed in implementations as communication, synchronization and sharing (depending upon the machine model)
  - Are the natural tasks of a suitable granularity?
    - Depending upon the machine, too many small tasks may incur high overheads in their interaction. Should they be collected together into super-tasks?
  - How should we assign tasks to processors?
    - In the presence of more tasks than processors, this is related to scaling down
    - The"owner compute" rule is natural for some algorithms which have been devised with a data-oriented partitioning
    - We need to ensure that tasks which interact can do so as (quickly) as possible.
- D&C is a very important technique and particularly helpful in PP since the recursive step can instead be parallelized
- Number of threads to be used:
  - `Runtime.getRuntime().availableProcessors()` might be the right amount but your program may not get access to all cores
  - too few threads are bad because core(s) is/are idle
  - too many threads can be bad because of the overhead[13]
- Sorting : If the array is sorted the following condition must hold (equal only if $A_i = A_j$):
  - $A_i \leq A_j$ for $i < j$
  - features of a sorting algorithm:
    - stable (duplicate data is allowed and the algorithm does not change duplicate's original ordering relative to each other), in-place ($\mathcal{O}(1)$ auxiliary space), non-comparison

[13]This depends on the actual overhead the language introduces (in Java rather big)

    - horrible $\Omega(n^2)$: bogo, stooge
    - simple $\mathcal{O}(n^2)$: insertion[14] , selection[15] , bubble, shell
    - fancier $\mathcal{O}(n \log n)$: heap, merge, quick sort (on average!)
    - specialized $\mathcal{O}(n)$: bubble, radix

- Linked Lists and Big Data:
  - Mergesort can very nicely work directly on linked lists
  - Heapsort and Quicksort do not;
  - InsertionSort and SelectionSort can too but slower
  - Mergesort also the sort of choice for external sorting

- Differences:
  - Quicksort and Heapsort jump all over the array
  - Mergesort scans linearly through arrays
  - In-memory sorting of blocks can be combined with larger sorts
  - Mergesort can leverage multiple disks

- PRAM model:
  - processors working in parallel, each is trying to access memory values
  - when designing algorithms, the type of memory access required needs to be considered
  - scheme for naming different types: [concurrent | exclusive]READ[concurrent | exclusive]WRITE[16]
  - typically CR are not a problem since the memory isnt changed whereas EW requires code to ensure writing is exclusive
  - PRAM is helpful to envision how it works and the needed data access pattern but isnt necessarily the way processors are arranged in practice

15 Java GUIs - MVC - Parallelism

Dont get me wrong, but Im having a hard time writing up this lecture

- (important) concepts:
  - MVC: (explained better later)
    - model (application domain, state and behaviour)
    - view (display layout and interaction views)
    - controller (user input, device interaction)
  - layout managers

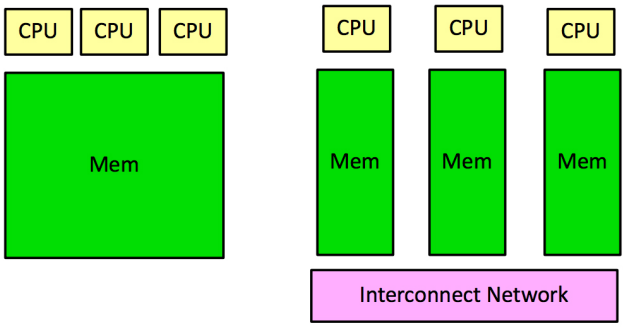
[14] At step k, put the k^{th} input element in the correct position among the first elements
[15] At step k, find the smallest element among the unsorted elements and put it at position k
[16] Abbreviated as E/C and R/W; ERCW is never considered

  - event-driven design (listener, worker[17] , callback, fire/handle)
  - GUI (painting)
- Swing threads:
  - initial[18]
  - event dispatch[19]
  - worker thread[20]
- MVC:
  - Model: complete, self-contained representation of object managed by the application, provides a number of services to manipulate the data, computation and persistence issues
  - View: tracks what is needed for a particular perspective of the data, presentation issues
  - Controller: gets input from the user, and uses appropriate information from the view to modify the model, interaction issues
  - Separation:
    * You can modify or create views without affecting the underlying model
    * The model should not need to know about all the kinds of views and interaction styles available for it

16 Concurrent Message Passing

- Goal: avoid (mutable) data sharing, instead use concurrent message passing (actor programming model) since many of the PP problems (so far) are due to shared state
- isolated mutable state:
  - state is mutable, but not shared
  - each thread/task has its private state
  - tasks cooperate with message passing
- Shared Memory Architecture (left side in image)
  - message passing and sharing state is used
  - message passing can be slower than sharing data yet is easier to implement and to reason about
- Distributed Memory Architecture (right side in image)
  - sharing state is challenging and often inefficient

[17] In Swing, this implements Runnable
[18] Main thread
[19] Drawing/painting the GUI
[20] Background thread, can be used for (heavy) computation to keep GUI responsive



  - using almost exclusively message passing
  - additional concerns such as failures

- Message passing works in both shared and distributed memory architectures making it more universal
  - Example: shared state counting (i.e. atomic counter) with `increase()` and `get()`:

    #1: one counter thread, the other threads ask for its value

    #2: every thread has its own (local) counter (Java: `ThreadLocal`), when sum is requested all threads return the value of their local counter
  - Example: bank account:
    * sequential programming: single balance
    * PP shared state: single balance & protection
    * PP distributed state: each thread has a local balance (budget), threads share balance coarsely

- distributed bank account (cont.): each task can operate independently, only communicate when needed

- Synchronous vs. Asynchronous messages:
  - Synchronous: send blocks until message is received (Java: `SynchronousQueue`)
  - Asynchronous:
    * Send does not block ("fire-and-forget")
    * placed into a buffer for receiver to get
    * Java: `BlockingQueue`; async as long as there is enough space (to prevent memory overflow)

- Concurrent Message Passing Programming Models:
  - Actors: state-full tasks communicating via messages (e.g. erlang)
  - Channels[21]:
    * Can be seen as a level of indirection over actors

[21] not an official term

        * Communicating Sequential Process (CSP)
        * (e.g. go)

- Go (by Google): language support for: lightweight tasks (aka goroutines), typed channels for task communications which are synchronous (unbuffered) by default

- Actor Programming Model:
  - A program is a set of actors that exchange (async) messages
  - Actor embodies:
    * State
    * Communication
    * Processing
  - An Actor may:
    * process messages
    * send messages
    * change local state
    * create new actors
  - Typically actors react to messages (Event-Driven Model)

- Event-Driven programming Model
  - A program is written as a set of handlers (typical application: GUI)

- Erlang:
  - Functional language
  - Developed for fault-tolerant applications (if no state is shared, recovering form errors becomes much easier)
  - Concurrent, following the actor model
  - Open-source

- Actor examples:
  - Distributor: forward received messages to a set of names in a round-robin fashion
    * State: an array of actors with the array index of the next actor to forward a message
    * Receive:
      · Messages → forward message and increase index (mod)
      · Control commands (e.g. add/remove actors)
  - Serializer:
    * Unordered input (e.g. due to different computation speed) → ordered output;
    * State: sorted list of received items, last item sent
    * Receive:

            - If we receive an item that is larger than the last item plus one, add it to the sorted list
            - If we receive an item that is equal to the past item plus one: send the received item plus all consecutive items form the last, and reset the last item

- Concurrent Message Passing in Java:
  - For simple applications, queues can be used
    - `SynchronousQueue`
      - `public class SyncronousQueue<E>`
      - synchronous/unbuffered
      - Can be thought of as a queue with zero capacity
  - Using Java queues can be difficult, especially of we want a large number of tasks

- Instead use Akka framework (written in Scala, interface for Java): follows the actor model (async messages), rich set of features (Hierarchical organizations of actors, etc.)[22]

- Akka actors example:
  - ping-pong: client sends n `PING`s to server which responds with `PONG` upon receiving back to sender, master stops execution when receiving `DONE`
  - Version 2 with restart on `DONE`: add a message type `SETUP` to the client passing the server actor reference and the count, if the client receives `SETUP` before `DONE` it can either wait for `DONE` and the restart, or discard the message.

- Collective operations:
  - Broadcast: send a message to all actors (related: multicast, sending a message to some actors); parallel broadcast using a tree where every parent forwards the message to its children until it reaches the leafs (top-down)
  - reduction: perform a computation from values of multiple nodes (e.g. balance of all bank accounts), using a tree where a parent receives the message from its children, performs operation and sends it to parent (bottom-up)

17 Data Parallel Programming

17.1 Data Parallel Programming

- Task vs Data parallelism:
  - Task:
    - Work is split into parts, by parallelizing the algorithm

[22] important methods to be overridden: `preStart()`, `onReceive()`

    - Very generic but cumbersome
    - Programmer describes parallel tasks
  - Data:
    - simultaneously applied operation on an aggregate of individual items (e.g. array)
    - declarative (= what not how), splitting up the data for parallelism
    - less generic
    - How is the responsibility of the run-time system

- Main Operations:
  - `map`:
    - Input: array (x), operation ($f(x)$)
    - Output: aggregate with applied operation ($f(x)$), e.g. $f(x_1), f(x_2), \ldots, f(x_n)$
    - parallel execution: split array into chunks and assign chunks to processors (scheduling)
    - generally more chunks leads to better load balancing (parallel slackness)
    - order of execution must not influence the result (since order depends on scheduling), given by pure functions (no side effects, same result for same argument)
  - `reduce` (reduction):
    - Input: aggregate (x) of data (e.g. an array), binary associative operator ($\bigoplus$) with an identity I
    - Output: $x_1 \bigoplus x_2 \bigoplus \cdots \bigoplus x_n$
    - Result stays the same for sequential vs. binary tree if operator is associative ($(a + b) + c = a + (b + c)$)
    - f operation is commutative ($a + b = b + a$)
    - Implementation:
      - Sequential: Accumulate result by iterating all elements
      - Parallel (D&C): Split into two parts, reduce each part recursively in parallel, stop recursion (cutoff value)
  - prefix scan: if it is an addition, it is a prefix sum
    - input: aggregate (x), binary associative operator ($\bigoplus$) with an identity I
    - output: ordered aggregate $(x_1, x_1 \bigoplus x_2, \ldots, x_1 \bigoplus x_2 \bigoplus \cdots \bigoplus x_n)$
  - `prefix scan` algorithm parallel version:
    - addition example:
      - 1st step is a reduction where two numbers are summed together and then pass their sum up the tree until it reaches the root i.e. bottom-up summing up all the values, two at a time

        - 2nd step is a down sweep where every node gets the sum of all the preceding leaf values passed whereas preceding is defined as pre-order
        - Have a look at slides 18 - 21 if in doubt
    - application of pre-scan:
        - line-of-sight, visible points (e.g. mountain tops) from a given observation point: point I is visible if no other point between I and the observer has a greater vertical distance $\theta_i = \arctan \frac{altitude_i - altitude_0}{i}$
        - compute angle for every point, do a max-pre-scan on angle array (e.g. 0,10,20,10,30,20 → 0,0,10,20,20,30), if $\theta_i > maxprevangle_i$ then $visible_i = true$ else $visible_i = false$
        - parallelizable parts:
            - for loop to compute angles
            - for loop to compute visibility can be written as parfors (parallel for loops)
    - `parfor`:
        - iterations can be performed in parallel: work partitioning → partition iteration space
        - Potential source of bugs if thought of as a sequential loop (data races; think factorial)

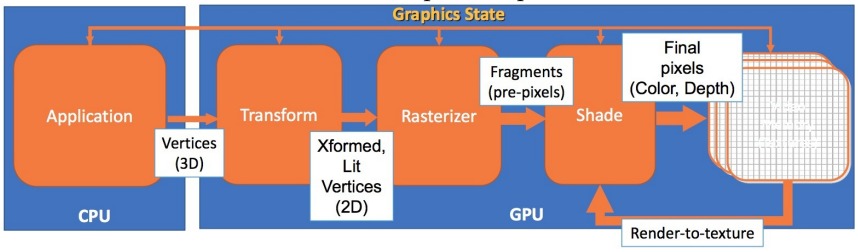
17.2 Data Parallel Programming in Java 8

- Functional programming crash course:
    - functions are first-class values (composition)
    - pure functions (immutability)
- such function are called lambdas or anonymous functions
- Functions as values:
    - Functions can be passed to other functions as arguments
    - Functions that accept other functions as arguments are called high-order functions, examples:
        - `map(f,list):f, (x0,x1,...)->(f(x0),f(x1),...)`
        - `filter(fn,list):f, (x0,x1,...)->(xi,xj,...)`
- Lambdas:
    - A lambda expression represents an anonymous function. It comprises of a set of parameters, a lambda operator (`->`) and a function body
    - Their type are functional interfaces (interfaces that specify a single method)
    - Make programming more convenient
- Data parallel programming in Java 8:
    - Done using streams

  - Providing means to manipulate data in a declarative way
  - Allowing for transparent parallel processing
- Menu example:
  - input: stream
  - output: stream, map/filter/etc. are applied
  - collect in the end, doesn't create a stream
  - overall translates a stream into a collection
- Parallel streams:
  - A stream can be turned into a parallel stream, just by invoking `.parallel()` on it
  - Split their elements up into chunks for different threads
  - implemented using Fork/Join Framework

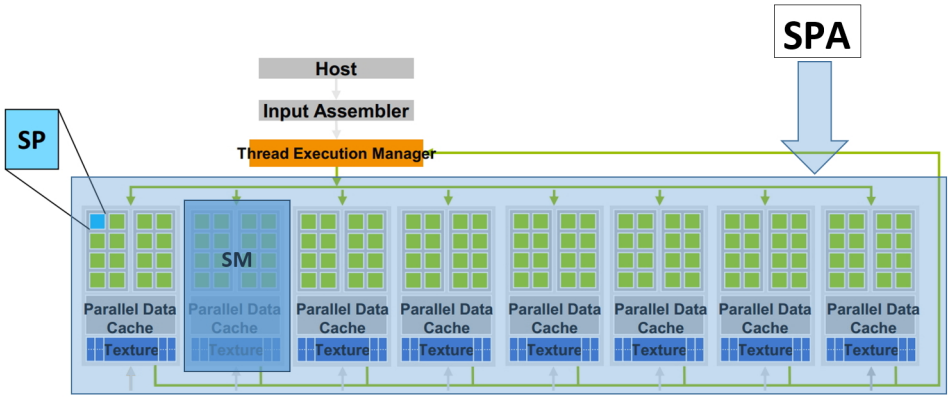
18 Intro to Massively Parallel Programming (GPGPU)

- Why Massively Parallel processors?
  - CPU vs. GPU:
    - Calculations: 4500 GFLOPS vs. 500 GFLOPS
    - Memory Bandwidth: 170 GB/s vs. 40 GB/s
  - Energy Crisis
    - Increasing clock speed no longer a valid option (Energy cons., Length of data lanes)
    - GPUs:
      - The massively parallel chip (GPU) might drain more power than a CPU
      - The power per flop is significantly reduced.
- Vocabulary:
  - Rendering: The process of generating an image from a 3D model
  - Vertex: The corner of a polygon (usually a triangle)
  - Pixel: Smallest addressable screen element
- GPU Fundamentals: The Fixed Graphics Pipeline



- GPU Pipeline:
  - Transform: Vertex Processor (multiple operate in parallel)
    - Transform from "World space" to "Image space"
    - Compute per-vertex lighting
  - Rasterizer
    - Convert geometric rep. (vertex) to image rep. (fragment)
      - Fragment = image fragment (Pixel + associated data: Color, depth, etc.)
    - Interpolate per-vertex quantities across pixels
  - Shade
    - Fragment Processors (multiple in parallel)
      - Compute a color for each pixel
      - Optionally read colors from textures
- The potential of GPUs for general purpose computation:
  - Power and flexibility of GPUs makes them an attractive platform
  - The problem: Difficult to use
    - GPU designed and designed for and driven by video games
      - Programming model is unusual & tied to computer graphics
      - Programming environment is tightly constrained
    - Underlying architectures are:
      - Inherently parallel
      - Rapidly evolving
      - Largely secret
    - Can't simply "port" code written for the CPU
    - Dealing with graphics API: Working with the corner cases of the graphics API
    - Addressing modes: Limited texture size/dimension
    - Shader capabilities: Limited outputs
    - Instruction sets: Lack of integer & bit ops.
    - Communication limited
      - Between pixels
      - Scatter `a[i]=p`
- Low Latency or High Throughput
  - CPU
    - Optimized for low-latency access to cached data sets
    - Control logic for out-of-order and speculative execution
  - GPU
    - Optimized for data-parallel, throughput computation
    - Architecture tolerant of memory latency
    - More transistors dedicated to computation

- GPGPU:
  - Modern GPU Architecture (GPGPU mode)
    - Processors execute computing threads
    - New operating mode/HW interface for computing
  - GPGPU Processor Terminology
    - SPA (device)
      - **S**treaming **P**rocessor **A**rray
    - SM
      - **S**treaming **M**ultiprocessor
      - Multi-threaded processor core
      - Fundamental processing unit for GPU thread block
    - SP
      - **S**treaming **P**rocessor
      - Scalar ALU for a single CUDA thread



  - **CUDA** -'Computer Unified Device Architecture'
    - General purpose programming model
      - User kicks off batches of threads on the GPU
      - GPU = dedicated super-threaded, massively data parallel co-processor
    - Targeted software stack
      - Computer oriented drivers, language, and tools
    - Driver for loading computation programs into GPU