

Lecture 1: introduction to multithreading

concurrency, parallelism, agents, threads, scheduler, threading models, interleaving execution, Amdahl's law, race condition, data race, deadlock, wait-for graph

Alexander Filatov
filatovaur@gmail.com

<https://github.com/Svazars/parallel-programming/blob/main/slides/pdf/l1.pdf>

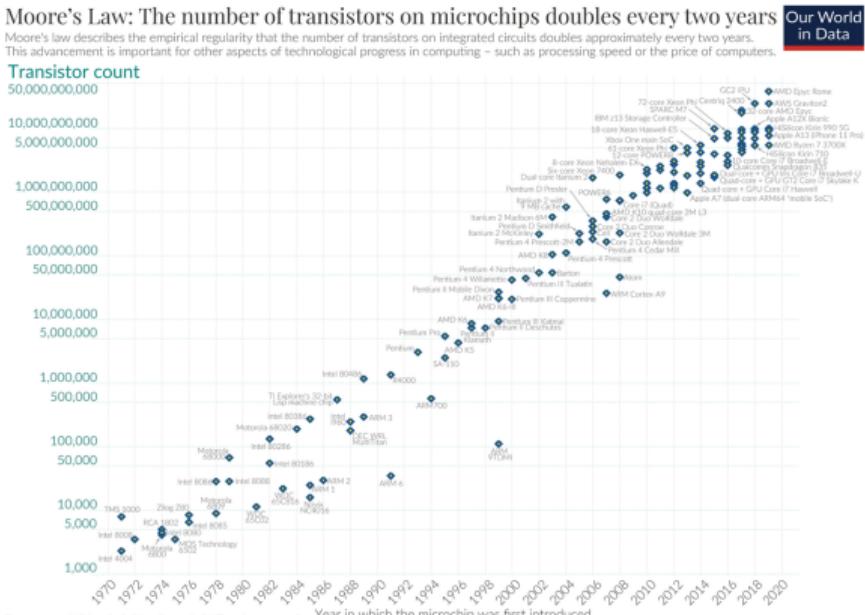
Lecture plan

- 1 Motivation
- 2 Concurrency and parallelism
- 3 Scheduler
- 4 Threads and processes
- 5 Multitasking and threading models
- 6 Concurrent problems
 - Embarrassingly parallel problems and Amdahl's law
 - Race condition
 - Data race
 - Visibility
 - Deadlock
 - Priority inversion
- 7 Summary

Motivation

Moore's law

https://en.wikipedia.org/wiki/Moore%27s_law#/media/File:Moore's_Law_Transistor_Count_1970-2020.png



Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count) Year in which the microchip was first introduced

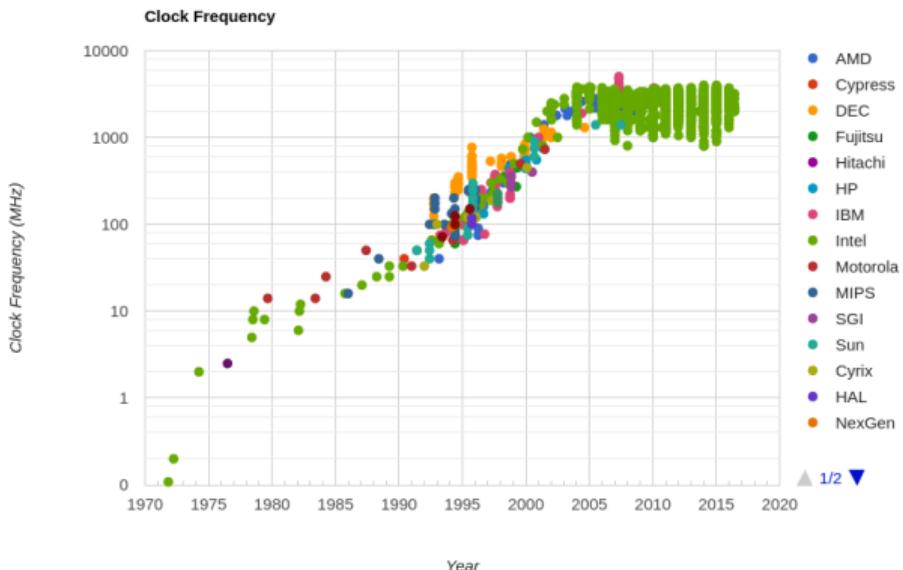
OurWorldInData.org - Research and data to make progress against the world's largest problems.

Licensed under CC-BY by the authors Hannah Ritchie and Max Roser.

Motivation

Clock frequency

http://cpudb.stanford.edu/visualize/clock_frequency.html



Question time

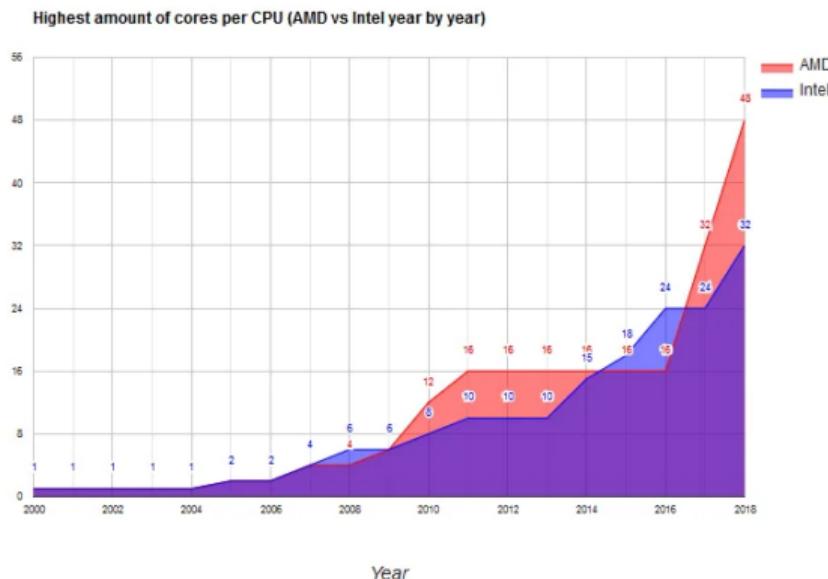
Question: Where are all these transistors?



Motivation

Core per CPU

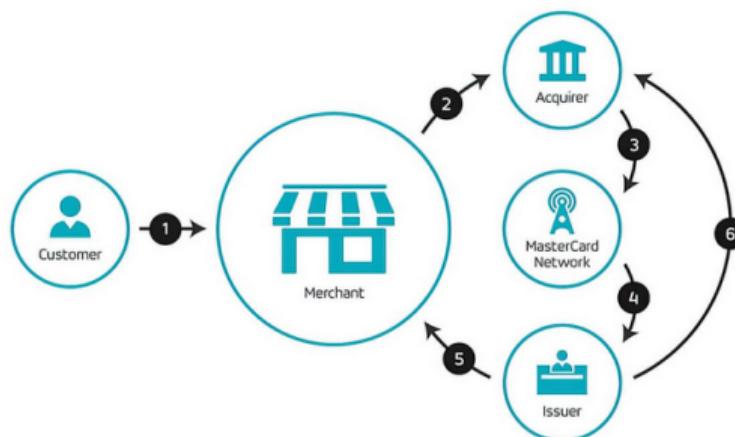
https://www.reddit.com/r/Amd/comments/6cu5ss/highest_amount_of_cores_per_cpu_amd_vs_intel_year



Motivation

Multi-agent systems

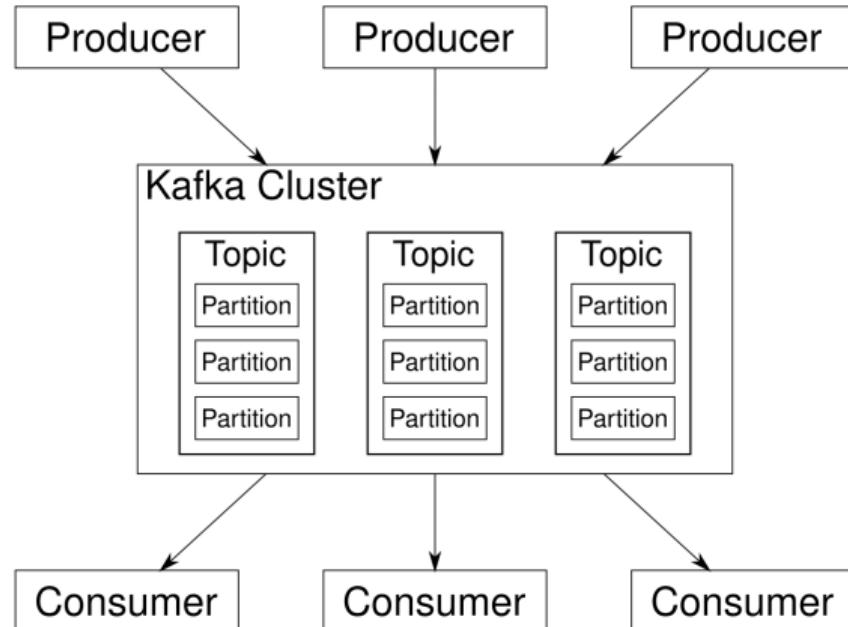
<https://sea.mastercard.com/en-region-sea/business/merchants/start-accepting/payment-process.html>



Motivation

Multi-agent systems

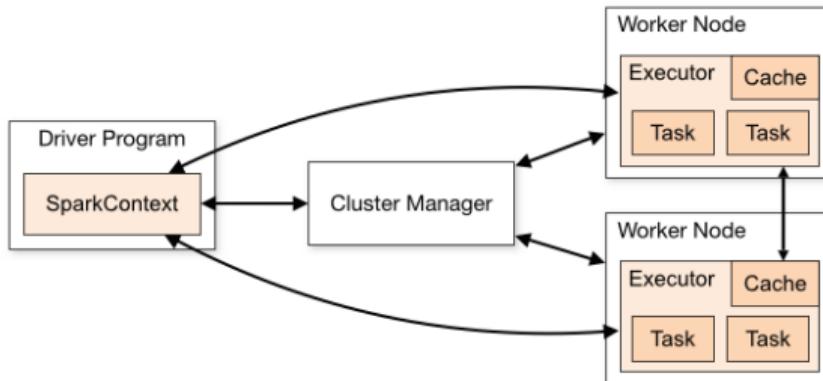
https://en.wikipedia.org/wiki/Apache_Kafka#/media/File:Overview_of_Apache_Kafka.svg



Motivation

Multi-agent systems

<https://spark.apache.org/docs/latest/cluster-overview.html>



Motivation

Multi-agent systems

<https://events19.linuxfoundation.org/wp-content/uploads/2018/07/dbueso-oss-japan19.pdf>

Locking Rules

struct eventpoll
spinlock_t lock
mutex lock
wait_queue_head_t wq
wait_queue_head_t poll_wq
list_head rlist
rb_root rbt
struct epitem *ovlist
wakeup_source *ws
user_struct *user
file *file
int visited
list_head visited_list_link

Mutex: serialization while transferring events to userspace

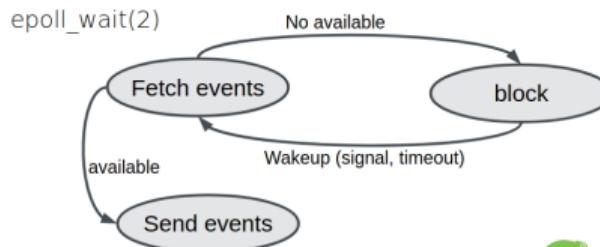
`copy_to_user` might block.

Protect `epoll_ctl(2)` operations, file exit, etc.

Spinlock: serialization inside IRQ context, cannot sleep.

Protects ready and *overflow* list manipulation.

(Must already hold the `ep->mutex`)



Common problems

- Many **independent** parts
- Different **speed**
- Need to **communicate** with each other
- Need to **coordinate** execution
- May **fail** spuriously

Agents

This course is about **communicating agents**. We will see

- Alice & Bob
- Processes in operating system
- Threads in operating system
- Separate computers that use networking to pass messages
- ...

Agents will try to:

- Decide who is in charge
- Pass data without corruption
- Coordinate execution of several steps in complicated task
- Find out how many agents take part in the communication
- ...

Different worlds

There are a lot of basic concepts behind the communication of independent agents.

But worlds are *different*:

- timings
 - minutes (conversation)
 - seconds (networking)
 - milliseconds (shared memory)
 - nanoseconds (CPU)
- delivery
 - possible distortion (misunderstanding)
 - possible loss (UDP packet)
 - visibility issue (not-yet-updated memory cell/stale value in CPU cache)
- denial-of-service
 - several people do phone call to the same person
 - network go offline
 - shared memory of single process in consistent (yet weakly ordered)
- ...

Lecture plan

- 1 Motivation
- 2 Concurrency and parallelism
- 3 Scheduler
- 4 Threads and processes
- 5 Multitasking and threading models
- 6 Concurrent problems
 - Embarrassingly parallel problems and Amdahl's law
 - Race condition
 - Data race
 - Visibility
 - Deadlock
 - Priority inversion
- 7 Summary

Question time

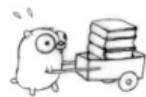
Question: "concurrency", "parallelism", who could translate both words to Russian?



Concurrency vs parallelism

Situations

Sequential and interruptible = concurrent¹

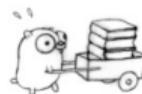


¹ <https://go.dev/talks/2012/waza.slide#12>

Concurrency vs parallelism

Situations

Sequential and interruptible = concurrent¹



Independent and simultaneous = parallel²



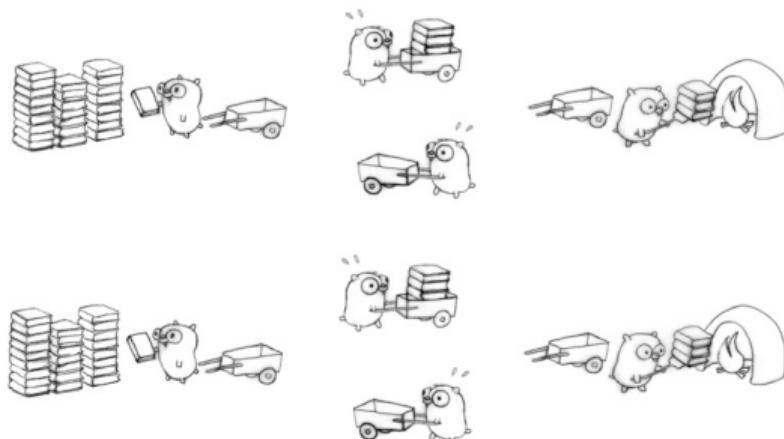
¹ <https://go.dev/talks/2012/waza.slide#12>

² <https://go.dev/talks/2012/waza.slide#15>

Concurrency vs parallelism

Two sides of the same medal

Real life is mixed³



Fun fact: real people in industry/academia may "interpret" parallelism/concurrency in different ways

³ <https://go.dev/talks/2012/waza.slide#22>

Concurrency vs parallelism

English

- Parallel
- Concurrent
- Independent
- Simultaneous
- At the same time

Question time

Question: "Parallel", "Concurrent", "Independent", "Simultaneous", "At the same time". Use one Russian word which would be the best translation for all 5 concepts.



Concurrency vs parallelism

English

- Parallel
- Concurrent
- Independent
- Simultaneous
- At the same time

Parallel – *could* execute simultaneously (independent, applicable to different executors)

Concurrent – *could* execute interchangeably (interruptible, applicable to the same executor)

Any real-life task combines parallel and concurrent parts⁴.

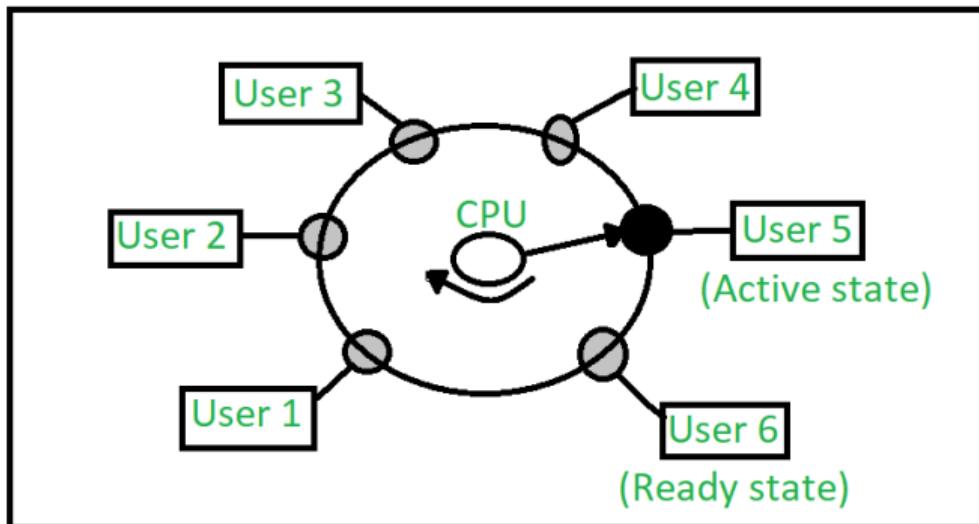
⁴

<https://stackoverflow.com/questions/1050222/what-is-the-difference-between-concurrency-and-parallelism>

Concurrency vs parallelism

Time-sharing for users

Single CPU, many users⁵

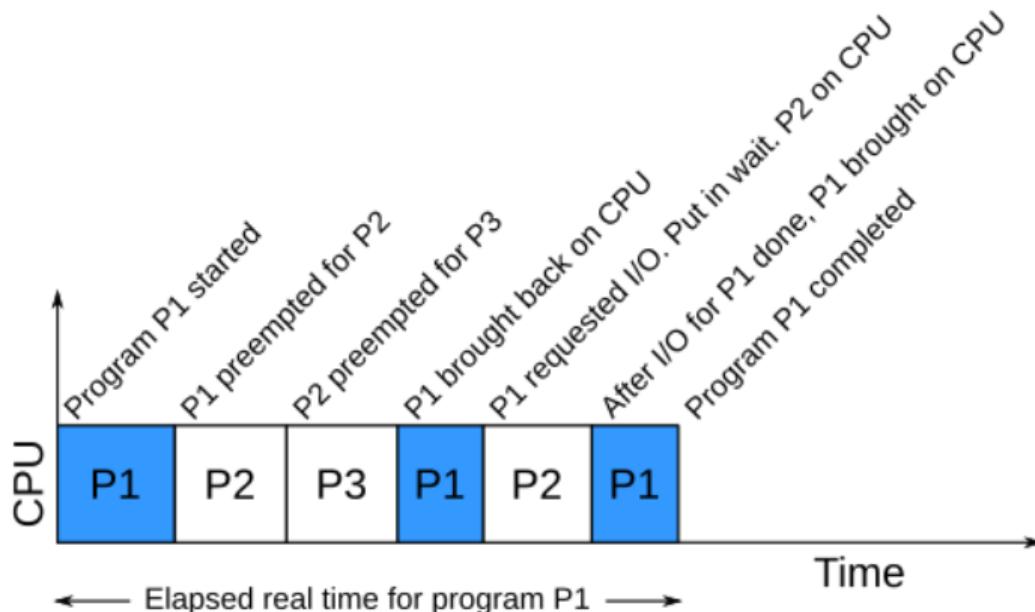


⁵ <https://www.geeksforgeeks.org/time-sharing-operating-system/>

Concurrency vs parallelism

Time-sharing for tasks

Single CPU, pre-emptible tasks⁶

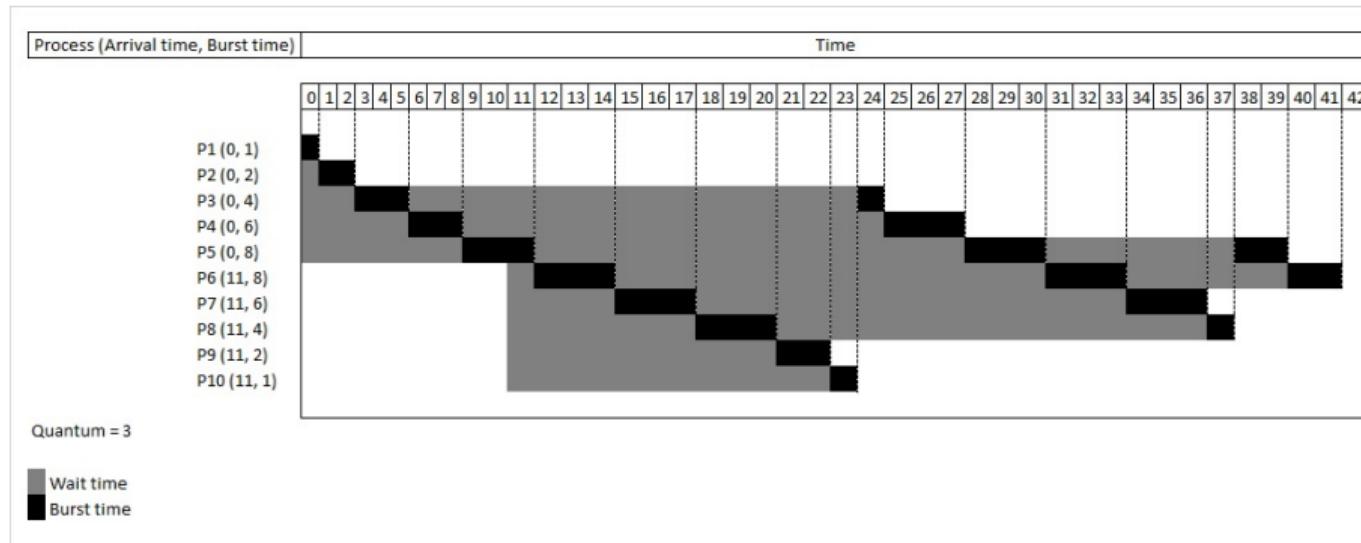


⁶ https://en.wikipedia.org/wiki/CPU_time

Concurrency vs parallelism

Time-sharing scheduling strategies

Round-robin scheduling⁷



⁷

https://en.wikipedia.org/wiki/Round-robin_scheduling

Concurrency vs parallelism

Conclusion

Concurrency and parallelism are two edges of the same phenomena.

In computer science (and in our course)

- parallelism
- concurrency
- interruptibility
- independence

have more formal meaning than in "usual" communication. Be aware.

Question time

Question: Multitasking, time-sharing, preemption, round-robin. We are going to talk about ...



Lecture plan

- 1 Motivation
- 2 Concurrency and parallelism
- 3 Scheduler
- 4 Threads and processes
- 5 Multitasking and threading models
- 6 Concurrent problems
 - Embarrassingly parallel problems and Amdahl's law
 - Race condition
 - Data race
 - Visibility
 - Deadlock
 - Priority inversion
- 7 Summary

Scheduler

Reminders

- Ivan Ugliansky, "Scheduling: from FCFS to EEVDF"

https://github.com/Svazars/parallel-programming/blob/main/slides/pdf-extra/algo_plus_oseSchedulers.pdf

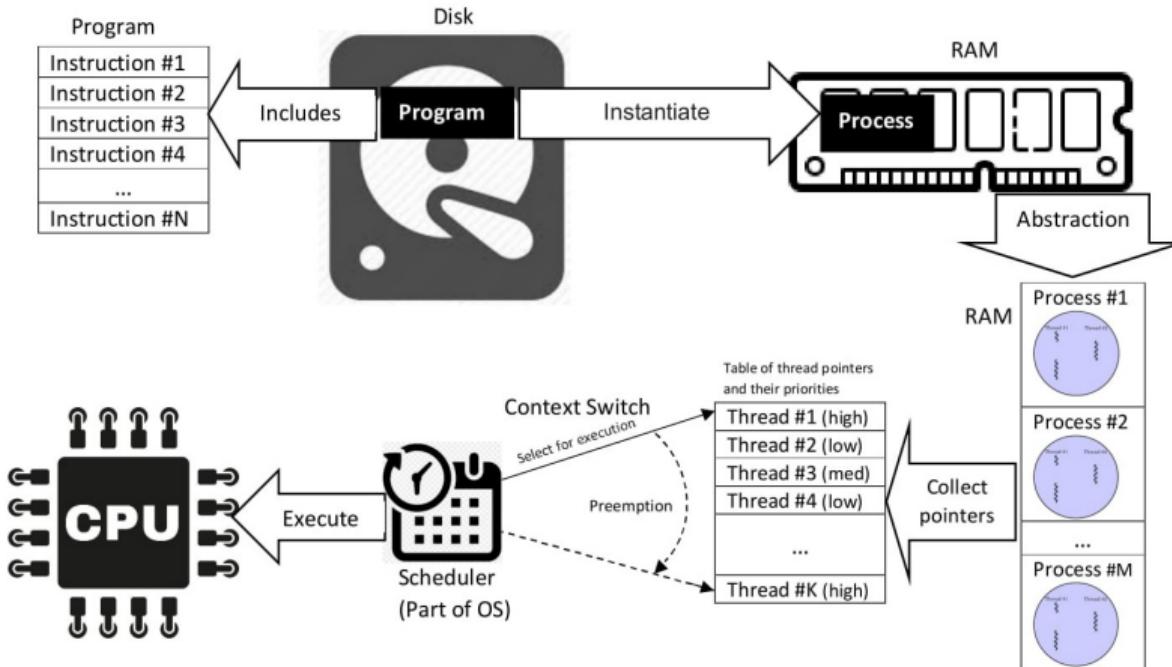
- "Operating Systems: Three Easy Pieces", "Scheduling: Introduction"

<https://pages.cs.wisc.edu/%7Eremzi/OSTEP/cpu-sched.pdf>

- [https://en.wikipedia.org/wiki/Process_\(computing\)](https://en.wikipedia.org/wiki/Process_(computing))

Scheduler

Problem overview



Scheduler

Problem overview

Scheduler – magic black box

- "knows and owns" every unit of scheduling (thread, process)
- may pre-empt execution of any unit (save state from CPU to memory)
- may enable execution of any pending unit (load state from memory to CPU)
- implements some scheduling policy (round-robin, shortest remaining time ...)

Scheduler

Problem overview

Scheduler – magic black box

- "knows and owns" every unit of scheduling (thread, process)
- may pre-empt execution of any unit (save state from CPU to memory)
- may enable execution of any pending unit (load state from memory to CPU)
- implements some scheduling policy (round-robin, shortest remaining time ...)

Save state / load state == switch CPU context of execution

Question time

Question: What is context switch on modern OS (e.g. Linux) and modern hardware with MMU (e.g. x86_64 intel Skylake)?



Scheduler

Context switch

Do not forget all the important data

- registers (general-purpose, floating-point, other)
- stack pointer
- instruction pointer
- segmentation/page tables
- translation lookaside buffer flush
- ...

Requires user-space → kernel space transition.

Scheduler

Context switch

Do not forget all the important data

- registers (general-purpose, floating-point, other)
- stack pointer
- instruction pointer
- segmentation/page tables
- translation lookaside buffer flush
- ...

Requires user-space \rightarrow kernel space transition.

Needs *amortization*.

Scheduler

Context switch

Do not forget all the important data

- registers (general-purpose, floating-point, other)
- stack pointer
- instruction pointer
- segmentation/page tables
- translation lookaside buffer flush
- ...

Requires user-space \rightarrow kernel space transition.

Needs *amortization*.

Scheduling quantum.

Scheduler

Scheduling quantum

Quantum may be arbitrary function of (current task, other tasks, state of OS).
Do not forget about

- frequency of context switches
- "price" of context switch
- thread/process priority
- "price" of CPU migration
- occupation of other processors
- ...

It is hard to trust timings^{8,9}.

⁸<https://shipilev.net/blog/2014/notrusting-nanotime>

⁹<https://pzemtsov.github.io/2017/07/23/the-slow-currenttimemillis.html>

Scheduler

Pre-emptive and cooperative multitasking

When to context switch?

Scheduler

Pre-emptive and cooperative multitasking

When to context switch?

Anytime anywhere:

- flexible
- easy-to-use model
- requires additional care
- has counter-examples
- relies on heuristics

When allowed to:

- fine-grained control
- nontrivial behaviour
- requires additional care
- has counter-examples
- relies on heuristics

Scheduler

Pre-emptive and cooperative multitasking

When to context switch?

Anytime anywhere:

- flexible
- easy-to-use model
- requires additional care
- has counter-examples
- relies on heuristics

When allowed to:

- fine-grained control
- nontrivial behaviour
- requires additional care
- has counter-examples
- relies on heuristics

In real environments it is always a hybrid solution¹⁰.

¹⁰The long road to lazy preemption: <https://lwn.net/Articles/994322/>

Scheduler

Goals

- In theory, there exist a *perfect* schedule
- In practice, almost any scheduling problem is NP-complete
- In applications, workload is dynamically generated on-the-fly

Scheduler

Goals

- In theory, there exist a *perfect* schedule
- In practice, almost any scheduling problem is NP-complete
- In applications, workload is dynamically generated on-the-fly

Realistic goals:

- Max *utilization*, not max *efficiency*
- Reasonable *latency*
- Soft/hard *real-time* constraints
- *Energy efficiency*

Question time

Question: Describe situation when *max utilization* scheduling contradicts *max efficiency* scheduling



Question time

Question: OS scheduler schedules **what?** Scheduler manages which OS **resource**?



Lecture plan

- 1 Motivation
- 2 Concurrency and parallelism
- 3 Scheduler
- 4 Threads and processes**
- 5 Multitasking and threading models
- 6 Concurrent problems
 - Embarrassingly parallel problems and Amdahl's law
 - Race condition
 - Data race
 - Visibility
 - Deadlock
 - Priority inversion
- 7 Summary

Question time

Question: Difference between "threads" and "processes" in one word?



Threads vs processes

Blast from the past

Process¹¹

- instance of computer program (program code and other stuff like .data, .rodata, .bss ...)
- owns resources (RAM, CPU, network ...) allocated by OS
- has logical and physical access permissions (filesystem, user capabilities ...)
- described by state (context)
- managed by OS
- **isolated** from other processes (virtual memory, namespaces ...)

¹¹ [https://en.wikipedia.org/wiki/Process_\(computing\)](https://en.wikipedia.org/wiki/Process_(computing))

Threads vs processes

Blast from the past

Thread¹²

- part of process (executes some code in some context)
- owns thread-specific resources (stack, TLS ...)
- has specific metadata (priority, TID ...)
- described by state (context)
- managed by OS scheduler
- **shares** memory with other threads

¹² [https://en.wikipedia.org/wiki/Thread_\(computing\)](https://en.wikipedia.org/wiki/Thread_(computing))

Threads vs processes

Bird-eye view

Processes and threads are **agents**

- different speed
- could communicate
- need coordination

Question time

Question: Threads need *more* or *less* coordination compared to processes?



Threads vs processes

Bird-eye view

Processes and threads are **agents**

- different speed
- could communicate
- need coordination

Threads vs processes

Bird-eye view

Processes and threads are **agents**

- different speed
- could communicate
- need coordination

In some sense, threads need *less* coordination (memory is already shared).

Threads vs processes

Bird-eye view

Processes and threads are **agents**

- different speed
- could communicate
- need coordination

In some sense, threads need *less* coordination (memory is already shared).

In some sense, threads need *more* coordination (memory is already shared).

Threads vs processes

Examples: process

```
echo "Sequential"  
wc 50_000_000.txt
```

```
real      0m 4,900s  
user      0m 4,212s  
sys       0m 0,240s
```

```
echo "Parallel"  
{ ( head -n 25000000 50_000_000.txt | wc) & }  
{ ( tail -n 25000000 50_000_000.txt | wc) & }  
wait
```

```
real      0m 2,323s  
user      0m 4,576s  
sys       0m 1,084s
```

Threads vs processes

Examples: process

```
echo "Sequential"
wc 50_000_000.txt

real      0m 4,900s
user      0m 4,212s
sys       0m 0,240s

echo "Parallel"
{ ( head -n 25000000 50_000_000.txt | wc) & }
{ ( tail -n 25000000 50_000_000.txt | wc) & }
wait

real      0m 2,323s
user      0m 4,576s
sys       0m 1,084s
```

- Create processes
- Wait completion
- Pass data via pipes, files, advanced IPC

Threads vs processes

Examples: Java threads

```
static long a, b;
static class MyThread extends Thread {
    private int idx; MyThread(int i) { this.idx = i; }
    @Override public void run() {
        for (long i = 0; i < 500_000; i++) {
            if (idx == 1) { a += func(i); }
            else           { b += func(i + 500_000); }
        }
    }
}
public static void main(String... args) throws Exception {
    Thread t1 = new MyThread(1); Thread t2 = new MyThread(2);
    t1.start(); t2.start(); // !!! not t1.run() !!!
    t1.join(); t2.join();
    System.out.println("Result = " + (a + b));
}
```

Your first homework

Your first homework

Read the docs

- <https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html>
- [https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#start\(\)](https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#start())
- [https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#join\(\)](https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#join())

Your first homework

Read the docs

- <https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html>
- [https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#start\(\)](https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#start())
- [https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#join\(\)](https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#join())

Yes, we use JDK 11 for all homeworks.

Your first homework

Read the docs

- <https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html>
- [https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#start\(\)](https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#start())
- [https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#join\(\)](https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#join())

Yes, we use JDK 11 for all homeworks. Yes, in 2026.

Your first homework

Read the docs

- <https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html>
- [https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#start\(\)](https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#start())
- [https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#join\(\)](https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#join())

Yes, we use JDK 11 for all homeworks. Yes, in 2026.

Anytime you see javase.docs URL on the lecture slides

Your first homework

Read the docs

- <https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html>
- [https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#start\(\)](https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#start())
- [https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#join\(\)](https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#join())

Yes, we use JDK 11 for all homeworks. Yes, in 2026.

Anytime you see javase.docs URL on the lecture slides

- I am free to ask you about corresponding Java API during the exam

Your first homework

Read the docs

- <https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html>
- [https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#start\(\)](https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#start())
- [https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#join\(\)](https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/lang/Thread.html#join())

Yes, we use JDK 11 for all homeworks. Yes, in 2026.

Anytime you see javase.docs URL on the lecture slides

- I am free to ask you about corresponding Java API during the exam

<https://github.com/Svazars/parallel-programming/blob/main/hw/block1/1.1/readme.markdown>

Homework, mail

Task 1.1 Create 3 Java programs for the following cases, explain results in several sentences.

Thread **A** starts thread **B** and joins. Uncaught exception happens in thread **B**.

- What happens in thread **B**?
- What happens in thread **A**?
- What if thread **C** joins thread **B** after exception happened?
- What if thread **D** joins thread **A**?

Question time

Question: Why would somebody use Java for parallel programming course, not C or C++?



Threads vs processes

Conclusion

From our course perspective:

- processes hold all the context and resources
- processes use many different parts of OS
- threads use ultra-fast shared memory for communication
- threads are minimal units eligible for OS scheduler

Almost all lectures will be about

- inter-process multi-threading
- inside high-level programming language
- run by multiprocessor hardware with MMU
- on non-real-time OS with pre-emptive multitasking

Threads vs processes

Conclusion

From our course perspective:

- processes hold all the context and resources
- processes use many different parts of OS
- threads use ultra-fast shared memory for communication
- threads are minimal units eligible for OS scheduler

Almost all lectures will be about

- inter-process multi-threading
- inside high-level programming language
- run by multiprocessor hardware with MMU
- on non-real-time OS with **pre-emptive multitasking**

Lecture plan

- 1 Motivation
- 2 Concurrency and parallelism
- 3 Scheduler
- 4 Threads and processes
- 5 Multitasking and threading models

- 6 Concurrent problems
 - Embarrassingly parallel problems and Amdahl's law
 - Race condition
 - Data race
 - Visibility
 - Deadlock
 - Priority inversion

- 7 Summary

Threading models

1:1 model

- N preemptible tasks
- Every task is allocated on designated computing agent

Threading models

1:1 model

- N preemptible tasks
- Every task is allocated on designated computing agent
- Examples:

Threading models

1:1 model

- N preemptible tasks
- Every task is allocated on designated computing agent
- Examples:
 - 1 Java thread – 1 OS thread
 - 1 OS thread – 1 CPU

Threading models

1:1 model

- N preemptible tasks
- Every task is allocated on designated computing agent
- Examples:
 - 1 Java thread – 1 OS thread
 - 1 OS thread – 1 CPU

N:1 model

- N preemptible tasks
- Single executor

Threading models

1:1 model

- N preemptible tasks
- Every task is allocated on designated computing agent
- Examples:
 - 1 Java thread – 1 OS thread
 - 1 OS thread – 1 CPU

N:1 model

- N preemptible tasks
- Single executor

N:M model

- N preemptible tasks
- Multiplexed over M computing agents. ($1 < M < N$)

Threading models

1:1 model

- N preemptible tasks
- Every task is allocated on designated computing agent
- Examples:
 - 1 Java thread – 1 OS thread
 - 1 OS thread – 1 CPU

N:1 model

- N preemptible tasks
- Single executor

N:M model

- N preemptible tasks
- Multiplexed over M computing agents. ($1 < M < N$)
- Examples:

Threading models

1:1 model

- N preemptible tasks
- Every task is allocated on designated computing agent
- Examples:
 - 1 Java thread – 1 OS thread
 - 1 OS thread – 1 CPU

N:1 model

- N preemptible tasks
- Single executor

N:M model

- N preemptible tasks
- Multiplexed over M computing agents. ($1 < M < N$)
- Examples:
 - thread pools (Lecture 3)
 - green threads, coroutines (Lecture 12)

N:1 threading model

N:1 threading model

- N preemptible tasks
- Single executor

N:1 threading model

N:1 threading model

- N preemptible tasks
- Single executor

Single-core OS

- N running processes
- Single CPU

N:1 threading model

N:1 threading model

- N preemptible tasks
- Single executor

Single-core OS

- N running processes
- Single CPU

Classic JVM run on single-core hardware

- N running Java threads
- Each Java thread mapped to corresponding OS thread (1:1)
- OS threads run on single CPU (N:1)

N:1 threading model

N:1 threading model

- N preemptible tasks
- Single executor

Single-core OS

- N running processes
- Single CPU

Classic JVM run on single-core hardware

- N running Java threads
- Each Java thread mapped to corresponding OS thread (1:1)
- OS threads run on single CPU (N:1)

Useful **model** for discussing possible behaviours of concurrent programs

Threading model: not enough

N:1 threading model

- N preemptible tasks
- Single executor

Threading model: not enough

N:1 threading model

- N preemptible tasks
- Single executor

Describes allocation of computing resources.

Threading model: not enough

N:1 threading model

- N preemptible tasks
- Single executor

Describes allocation of computing resources.

What about interaction between tasks?

Threading model: not enough

N:1 threading model

- N preemptible tasks
- Single executor

Describes allocation of computing resources.

What about interaction between tasks?

Need additional information

- guarantees to memory update visibility?
- expectations about scheduling policy?
- cross-thread interactions ordering?

Interleaving model

N:1 threading model

- N preemptible tasks
- Single executor

Interleaving model

N:1 threading model

- N preemptible tasks
- Single executor

Preemption could happen

- At any place (any machine instruction)
- At any time (every femtosecond)
- For arbitrary long time (undefined scheduling policy)

Interleaving model

N:1 threading model

- N preemptible tasks
- Single executor

Preemption could happen

- At any place (any machine instruction)
- At any time (every femtosecond)
- For arbitrary long time (undefined scheduling policy)

Executed instructions instantly affect whole computing system

- All subsequent instructions see up-to-date memory state
- All threads observe the same up-to-date memory state
- All events are totally ordered on a timeline

Interleaving model

N:1 threading model

- N preemptible tasks
- Single executor

Preemption could happen

- At any place (any machine instruction)
- At any time (every femtosecond)
- For arbitrary long time (undefined scheduling policy)

Executed instructions instantly affect whole computing system

- All subsequent instructions see up-to-date memory state
- All threads observe the same up-to-date memory state
- All events are totally ordered on a timeline

This is **simplified** model of concurrent execution. We will use it up to Lecture 6.

Question time

Question: What is the difference between N:1 threading model and describing concurrent system using interleavings?



Interleaving model: visualization

```
static int x, y;

class A extends Thread {
    public void run() {
        int a_x = x;      // A.1
        int a_y = y;      // A.2
        x++;             // A.3
        y++;             // A.4
        log(a_x, a_y);  // A.5
    }
}

class B extends Thread {
    public void run() {
        int b_x = x;      // B.1
        int b_y = y;      // B.2
        x++;             // B.3
        y++;             // B.4
        log(b_x, b_y);  // B.5
    }
}
```

Interleaving model: visualization

```
static int x, y;

class A extends Thread {
    public void run() {
        int a_x = x;      // A.1
        int a_y = y;      // A.2
        x++;             // A.3
        y++;             // A.4
        log(a_x, a_y);  // A.5
    }
}

class B extends Thread {
    public void run() {
        int b_x = x;      // B.1
        int b_y = y;      // B.2
        x++;             // B.3
        y++;             // B.4
        log(b_x, b_y);  // B.5
    }
}
```

Interleaving model: visualization

```
static int x, y;

class A extends Thread {
    public void run() {
        int a_x = x;      // A.1
        int a_y = y;      // A.2
        x++;             // A.3
        y++;             // A.4
        log(a_x, a_y);  // A.5
    }
}

class B extends Thread {
    public void run() {
        int b_x = x;      // B.1
        int b_y = y;      // B.2
        x++;             // B.3
        y++;             // B.4
        log(b_x, b_y);  // B.5
    }
}
```

Interleaving model: visualization

```
static int x, y;

class A extends Thread {
    public void run() {
        int a_x = x;      // A.1
        int a_y = y;      // A.2
        x++;             // A.3
        y++;             // A.4
        log(a_x, a_y);  // A.5
    }
}

class B extends Thread {
    public void run() {
        int b_x = x;      // B.1
        int b_y = y;      // B.2
        x++;             // B.3
        y++;             // B.4
        log(b_x, b_y);  // B.5
    }
}
```

Interleaving model: visualization

```
static int x, y;

class A extends Thread {
    public void run() {
        int a_x = x;      // A.1
        int a_y = y;      // A.2
        x++;             // A.3
        y++;             // A.4
        log(a_x, a_y);  // A.5
    }
}

class B extends Thread {
    public void run() {
        int b_x = x;      // B.1
        int b_y = y;      // B.2
        x++;             // B.3
        y++;             // B.4
        log(b_x, b_y);  // B.5
    }
}
```

Interleaving model: visualization

```
static int x, y;

class A extends Thread {
    public void run() {
        int a_x = x;      // A.1
        int a_y = y;      // A.2
        x++;             // A.3
        y++;             // A.4
        log(a_x, a_y);  // A.5
    }
}

class B extends Thread {
    public void run() {
        int b_x = x;      // B.1
        int b_y = y;      // B.2
        x++;             // B.3
        y++;             // B.4
        log(b_x, b_y);  // B.5
    }
}
```

A.1->...>A.5. a_x = 0, a_y = 0;

Interleaving model: visualization

```
static int x, y;

class A extends Thread {
    public void run() {
        int a_x = x;      // A.1
        int a_y = y;      // A.2
        x++;             // A.3
        y++;             // A.4
        log(a_x, a_y);  // A.5
    }
}

class B extends Thread {
    public void run() {
        int b_x = x;      // B.1
        int b_y = y;      // B.2
        x++;             // B.3
        y++;             // B.4
        log(b_x, b_y);  // B.5
    }
}
```

A.1->...>A.5. a_x = 0, a_y = 0;

Interleaving model: visualization

```
static int x, y;

class A extends Thread {
    public void run() {
        int a_x = x;      // A.1
        int a_y = y;      // A.2
        x++;             // A.3
        y++;             // A.4
        log(a_x, a_y);  // A.5
    }
}

class B extends Thread {
    public void run() {
        int b_x = x;      // B.1
        int b_y = y;      // B.2
        x++;             // B.3
        y++;             // B.4
        log(b_x, b_y);  // B.5
    }
}
```

A.1->...>A.5. a_x = 0, a_y = 0;

Interleaving model: visualization

```
static int x, y;

class A extends Thread {
    public void run() {
        int a_x = x;      // A.1
        int a_y = y;      // A.2
        x++;             // A.3
        y++;             // A.4
        log(a_x, a_y); // A.5
    }
}

class B extends Thread {
    public void run() {
        int b_x = x;      // B.1
        int b_y = y;      // B.2
        x++;             // B.3
        y++;             // B.4
        log(b_x, b_y); // B.5
    }
}
```

A.1->...>A.5. a_x = 0, a_y = 0;

Interleaving model: visualization

```
static int x, y;

class A extends Thread {
    public void run() {
        int a_x = x;      // A.1
        int a_y = y;      // A.2
        x++;             // A.3
        y++;             // A.4
        log(a_x, a_y);  // A.5
    }
}

class B extends Thread {
    public void run() {
        int b_x = x;      // B.1
        int b_y = y;      // B.2
        x++;             // B.3
        y++;             // B.4
        log(b_x, b_y);  // B.5
    }
}
```

A.1->...>A.5. a_x = 0, a_y = 0;

Interleaving model: visualization

```
static int x, y;

class A extends Thread {
    public void run() {
        int a_x = x;      // A.1
        int a_y = y;      // A.2
        x++;             // A.3
        y++;             // A.4
        log(a_x, a_y);  // A.5
    }
}

class B extends Thread {
    public void run() {
        int b_x = x;      // B.1
        int b_y = y;      // B.2
        x++;             // B.3
        y++;             // B.4
        log(b_x, b_y);  // B.5
    }
}
```

A.1->...->A.5. a_x = 0, a_y = 0;

A.1->...->A.5->B.1->...->B.5. a_x = 0, a_y = 0, b_x = 1, b_y = 1;

Interleaving model: single execution trace

```
class A extends Thread {  
    public void run() {  
        int a_x = x;      // A.1  
        int a_y = y;      // A.2  
        x++;            // A.3  
        y++;            // A.4  
        log(a_x, a_y); // A.5  
    }  
}  
  
class B extends Thread {  
    public void run() {  
        int b_x = x;      // B.1  
        int b_y = y;      // B.2  
        x++;            // B.3  
        y++;            // B.4  
        log(b_x, b_y); // B.5  
    }  
}
```

Interleaving model: single execution trace

```
class A extends Thread {  
    public void run() {  
        int a_x = x;      // A.1  
        int a_y = y;      // A.2  
        x++;            // A.3  
        y++;            // A.4  
        log(a_x, a_y); // A.5  
    }  
}  
  
class B extends Thread {  
    public void run() {  
        int b_x = x;      // B.1  
        int b_y = y;      // B.2  
        x++;            // B.3  
        y++;            // B.4  
        log(b_x, b_y); // B.5  
    }  
}
```

Interleaving model: single execution trace

```
class A extends Thread {  
    public void run() {  
        int a_x = x;      // A.1  
        int a_y = y;      // A.2  
        x++;             // A.3  
        y++;             // A.4  
        log(a_x, a_y); // A.5  
    }  
}  
  
class B extends Thread {  
    public void run() {  
        int b_x = x;      // B.1  
        int b_y = y;      // B.2  
        x++;             // B.3  
        y++;             // B.4  
        log(b_x, b_y); // B.5  
    }  
}
```

Interleaving model: single execution trace

```
class A extends Thread {  
    public void run() {  
        int a_x = x;      // A.1  
        int a_y = y;      // A.2  
        x++;             // A.3  
        y++;             // A.4  
        log(a_x, a_y); // A.5  
    }  
}
```

```
class B extends Thread {  
    public void run() {  
        int b_x = x;      // B.1  
        int b_y = y;      // B.2  
        x++;             // B.3  
        y++;             // B.4  
        log(b_x, b_y); // B.5  
    }  
}
```

Interleaving model: single execution trace

```
class A extends Thread {          class B extends Thread {  
    public void run() {           public void run() {  
        int a_x = x;      // A.1     int b_x = x;      // B.1  
        int a_y = y;      // A.2     int b_y = y;      // B.2  
        x++;             // A.3     x++;             // B.3  
        y++;             // A.4     y++;             // B.4  
        log(a_x, a_y);   // A.5     log(b_x, b_y);   // B.5  
    }                           }  
}
```

Interleaving model: single execution trace

```
class A extends Thread {  
    public void run() {  
        int a_x = x;      // A.1  
        int a_y = y;      // A.2  
        x++;             // A.3  
        y++;             // A.4  
        log(a_x, a_y); // A.5  
    }  
}  
  
class B extends Thread {  
    public void run() {  
        int b_x = x;      // B.1  
        int b_y = y;      // B.2  
        x++;             // B.3  
        y++;             // B.4  
        log(b_x, b_y); // B.5  
    }  
}
```

Interleaving model: single execution trace

```
class A extends Thread {  
    public void run() {  
        int a_x = x;      // A.1  
        int a_y = y;      // A.2  
        x++;             // A.3  
        y++;             // A.4  
        log(a_x, a_y); // A.5  
    }  
}
```

```
class B extends Thread {  
    public void run() {  
        int b_x = x;      // B.1  
        int b_y = y;      // B.2  
        x++;             // B.3  
        y++;             // B.4  
        log(b_x, b_y); // B.5  
    }  
}
```

Interleaving model: single execution trace

```
class A extends Thread {  
    public void run() {  
        int a_x = x;      // A.1  
        int a_y = y;      // A.2  
        x++;             // A.3  
        y++;             // A.4  
        log(a_x, a_y); // A.5  
    }  
}  
  
class B extends Thread {  
    public void run() {  
        int b_x = x;      // B.1  
        int b_y = y;      // B.2  
        x++;             // B.3  
        y++;             // B.4  
        log(b_x, b_y); // B.5  
    }  
}
```

A1->B1->A2->B2->A3->...->A5: a_x = 0, a_y = 0;

Interleaving model: single execution trace

```
class A extends Thread {  
    public void run() {  
        int a_x = x;      // A.1  
        int a_y = y;      // A.2  
        x++;             // A.3  
        y++;             // A.4  
        log(a_x, a_y); // A.5  
    }  
}
```

```
class B extends Thread {  
    public void run() {  
        int b_x = x;      // B.1  
        int b_y = y;      // B.2  
        x++;             // B.3  
        y++;             // B.4  
        log(b_x, b_y); // B.5  
    }  
}
```

A1->B1->A2->B2->A3->...->A5: a_x = 0, a_y = 0;

Interleaving model: single execution trace

```
class A extends Thread {  
    public void run() {  
        int a_x = x;      // A.1  
        int a_y = y;      // A.2  
        x++;             // A.3  
        y++;             // A.4  
        log(a_x, a_y); // A.5  
    }  
}  
  
class B extends Thread {  
    public void run() {  
        int b_x = x;      // B.1  
        int b_y = y;      // B.2  
        x++;             // B.3  
        y++;             // B.4  
        log(b_x, b_y); // B.5  
    }  
}
```

A1->B1->A2->B2->A3->...->A5: a_x = 0, a_y = 0;

Interleaving model: single execution trace

```
class A extends Thread {  
    public void run() {  
        int a_x = x;      // A.1  
        int a_y = y;      // A.2  
        x++;            // A.3  
        y++;            // A.4  
        log(a_x, a_y); // A.5  
    }  
}  
  
class B extends Thread {  
    public void run() {  
        int b_x = x;      // B.1  
        int b_y = y;      // B.2  
        x++;            // B.3  
        y++;            // B.4  
        log(b_x, b_y); // B.5  
    }  
}
```

A1->B1->A2->B2->A3->...->A5: a_x = 0, a_y = 0;

A1->B1->A2->B2->A3->...->A5->...->B5: a_x = 0, a_y = 0, b_x = 0, b_y = 0;

Interleaving model: possible execution results

```
class A extends Thread {          class B extends Thread {  
    public void run() {           public void run() {  
        int a_x = x;             int b_x = x;  
        int a_y = y;             int b_y = y;  
        x++;                   x++;  
        y++;                   y++;  
        log(a_x, a_y);         log(b_x, b_y);  
    }  
}
```

a_x = 0, a_y = 0, b_x = 0, b_y = 0
a_x = 0, a_y = 0, b_x = 0, b_y = 1
a_x = 0, a_y = 0, b_x = 1, b_y = 0
a_x = 0, a_y = 0, b_x = 1, b_y = 1
...

Interleaving model: key concepts

Concurrent execution trace:

- All operations inside thread ordered sequentially
- All operations across all threads are totally ordered on timeline
- Single deterministic result of execution

Non-determinism:

- Concurrent program may have **many** execution traces.
- Concurrent program may have **many** results of execution.

Question time

Question: single-threaded program that have many execution traces?



Question time

Question: concurrent program with many execution traces but only one result of execution?



Question time

Question: concurrent program with infinite number of execution traces?



Interleaving model: homework

Homework, mail

Task 1.2. For given multithreaded program and execution result provide either

- concurrent execution trace ($A.1 \rightarrow A.2 \rightarrow B.1 \dots$) or
- proof of impossibility

<https://github.com/Svazars/parallel-programming/blob/main/hw/block1/1.2/readme.markdown>

Homework, mail

Task 1.3. For given multithreaded program:

- provide all possible execution results
- provide only one execution trace per result
- prove exhaustiveness of your answer

<https://github.com/Svazars/parallel-programming/blob/main/hw/block1/1.3/readme.markdown>

Our main enemy through the course

Our main enemy through the course

Non-determinism

Our main enemy through the course

Non-determinism: concurrent program may have **many** execution traces.

Our main enemy through the course

Non-determinism: concurrent program may have **many** execution traces.

- Hard to reason about all possible memory states

Our main enemy through the course

Non-determinism: concurrent program may have **many** execution traces.

- Hard to reason about all possible memory states
- Hard to define and guarantee program invariants

Our main enemy through the course

Non-determinism: concurrent program may have **many** execution traces.

- Hard to reason about all possible memory states
- Hard to define and guarantee program invariants
- Hard to reproduce erroneous behavior

Our main enemy through the course

Non-determinism: concurrent program may have **many** execution traces.

- Hard to reason about all possible memory states
- Hard to define and guarantee program invariants
- Hard to reproduce erroneous behavior
- Hard to verify concurrent bug is fixed

Our main enemy through the course

Non-determinism: concurrent program may have **many** execution traces.

- Hard to reason about all possible memory states
- Hard to define and guarantee program invariants
- Hard to reproduce erroneous behavior
- Hard to verify concurrent bug is fixed
- Hard to prove correctness

Our main enemy through the course

Non-determinism: concurrent program may have **many** execution traces.

- Hard to reason about all possible memory states
- Hard to define and guarantee program invariants
- Hard to reproduce erroneous behavior
- Hard to verify concurrent bug is fixed
- Hard to prove correctness

Solution:

Our main enemy through the course

Non-determinism: concurrent program may have **many** execution traces.

- Hard to reason about all possible memory states
- Hard to define and guarantee program invariants
- Hard to reproduce erroneous behavior
- Hard to verify concurrent bug is fixed
- Hard to prove correctness

Solution: study hard!

Our main enemy through the course

Non-determinism: concurrent program may have **many** execution traces.

- Hard to reason about all possible memory states
- Hard to define and guarantee program invariants
- Hard to reproduce erroneous behavior
- Hard to verify concurrent bug is fixed
- Hard to prove correctness

Solution: study hard!

- Write and debug concurrent programs (Lectures 2-5)

Our main enemy through the course

Non-determinism: concurrent program may have **many** execution traces.

- Hard to reason about all possible memory states
- Hard to define and guarantee program invariants
- Hard to reproduce erroneous behavior
- Hard to verify concurrent bug is fixed
- Hard to prove correctness

Solution: study hard!

- Write and debug concurrent programs (Lectures 2-5)
- Use formalization for concurrent execution (Lectures 6-8)

Our main enemy through the course

Non-determinism: concurrent program may have **many** execution traces.

- Hard to reason about all possible memory states
- Hard to define and guarantee program invariants
- Hard to reproduce erroneous behavior
- Hard to verify concurrent bug is fixed
- Hard to prove correctness

Solution: study hard!

- Write and debug concurrent programs (Lectures 2-5)
- Use formalization for concurrent execution (Lectures 6-8)
- Go to hardware-level (Lecture 9)

Our main enemy through the course

Non-determinism: concurrent program may have **many** execution traces.

- Hard to reason about all possible memory states
- Hard to define and guarantee program invariants
- Hard to reproduce erroneous behavior
- Hard to verify concurrent bug is fixed
- Hard to prove correctness

Solution: study hard!

- Write and debug concurrent programs (Lectures 2-5)
- Use formalization for concurrent execution (Lectures 6-8)
- Go to hardware-level (Lecture 9)
- Go to semantic level (Lecture 10)

Our main enemy through the course

Non-determinism: concurrent program may have **many** execution traces.

- Hard to reason about all possible memory states
- Hard to define and guarantee program invariants
- Hard to reproduce erroneous behavior
- Hard to verify concurrent bug is fixed
- Hard to prove correctness

Solution: study hard!

- Write and debug concurrent programs (Lectures 2-5)
- Use formalization for concurrent execution (Lectures 6-8)
- Go to hardware-level (Lecture 9)
- Go to semantic level (Lecture 10)
- ... and beyond (Lectures 11+)

Concurrency: tips and tricks

Concurrency: tips and tricks

- If concurrent tests pass on your local machine

Concurrency: tips and tricks

- If concurrent tests pass on your local machine
 - no guarantee your program is correct.

Concurrency: tips and tricks

- If concurrent tests pass on your local machine
 - no guarantee your program is correct.
- If some concurrent test fails

Concurrency: tips and tricks

- If concurrent tests pass on your local machine
 - no guarantee your program is correct.
- If some concurrent test fails
 - maybe there is a bug in test itself.

Concurrency: tips and tricks

- If concurrent tests pass on your local machine
 - no guarantee your program is correct.
- If some concurrent test fails
 - maybe there is a bug in test itself.
- If interleaving model explains a bug

Concurrency: tips and tricks

- If concurrent tests pass on your local machine
 - no guarantee your program is correct.
- If some concurrent test fails
 - maybe there is a bug in test itself.
- If interleaving model explains a bug
 - you must fix it.

Concurrency: tips and tricks

- If concurrent tests pass on your local machine
 - no guarantee your program is correct.
- If some concurrent test fails
 - maybe there is a bug in test itself.
- If interleaving model explains a bug
 - you must fix it. **Always.**

Concurrency: tips and tricks

- If concurrent tests pass on your local machine
 - no guarantee your program is correct.
- If some concurrent test fails
 - maybe there is a bug in test itself.
- If interleaving model explains a bug
 - you must fix it. **Always.**
- If interleaving model proves correctness of your program

Concurrency: tips and tricks

- If concurrent tests pass on your local machine
 - no guarantee your program is correct.
- If some concurrent test fails
 - maybe there is a bug in test itself.
- If interleaving model explains a bug
 - you must fix it. **Always.**
- If interleaving model proves correctness of your program
 - still run stress-tests.

Lecture plan

- 1 Motivation
- 2 Concurrency and parallelism
- 3 Scheduler
- 4 Threads and processes
- 5 Multitasking and threading models
- 6 Concurrent problems
 - Embarrassingly parallel problems and Amdahl's law
 - Race condition
 - Data race
 - Visibility
 - Deadlock
 - Priority inversion
- 7 Summary

Concurrent building blocks you know so far

- ➊ Create new thread and start it
- ➋ Modify fields concurrently
- ➌ Join thread

Concurrent building blocks you know so far

- ➊ Create new thread and start it
- ➋ Modify fields concurrently
- ➌ Join thread

Combining 1 and 2:

- Solve "easy" parallel problems
- Encounter logic errors (race conditions)
- Encounter concurrent memory access effects (data races)

Concurrent building blocks you know so far

- ➊ Create new thread and start it
- ➋ Modify fields concurrently
- ➌ Join thread

Combining 1 and 2:

- Solve "easy" parallel problems
- Encounter logic errors (race conditions)
- Encounter concurrent memory access effects (data races)

Using 3:

- Encounter visibility bugs (stale value)
- Encounter no-progress blocking (deadlock)
- Observe slow-progress issues (priority inversion)

Lecture plan

- 1 Motivation
- 2 Concurrency and parallelism
- 3 Scheduler
- 4 Threads and processes
- 5 Multitasking and threading models
- 6 Concurrent problems
 - Embarrassingly parallel problems and Amdahl's law
 - Race condition
 - Data race
 - Visibility
 - Deadlock
 - Priority inversion
- 7 Summary

Embarrassingly parallel problems

Introduction

Synonyms:

- Embarrassingly parallel
- Embarrassingly parallelizable
- Perfectly parallel
- Delightfully parallel
- Pleasingly parallel

Key properties:

- Granularity
- Minimal coordination

Question time

Question: Any ideas for embarrassingly parallel problems?



Embarrassingly parallel problems

Examples

- function applied to collection of items (*map*)
 - ray tracing
 - word count in independent files
 - proof-of-work cryptocurrency
 - bioinformatics search (BLAST etc)
 - Discrete Fourier transform
- associative operation applied to large array (order-independent *reduce*)
 - sum of elements in integer array
 - word count for all books in e-library
- ...

Amdahl's law

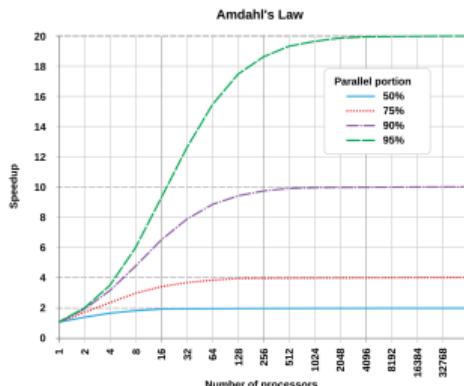
Key ideas

Any problem consists of *serial* part and *parallel* part.

Speed-up of parallel part depends on computational resources. Serial part is "fixed work".

- **Diminishing Returns:** beyond certain point, adding more processors doesn't significantly increase speedup
- **Limited Speedup:** problem cannot be solved faster than serial part

https://en.wikipedia.org/wiki/Amdahl%27s_law



Amdahl's law

Examples

- Programmer enhances a part of the code that represents 10% of the total execution time. This part starts to work 10 000 times faster. What is total speedup of a program?
- Problem could be split into two parts: A and B. A is serial, B is parallel. On single CPU, A takes 50 minutes, B takes 250 minutes. How many CPUs do you need to solve the problem in 100 minutes (achieve 3x speed-up)?
- Prepare an example where 10x speed-up could be achieved by using 100 CPUs only.

Amdahl's law

Examples

- Programmer enhances a part of the code that represents 10% of the total execution time. This part starts to work 10 000 times faster. What is total speedup of a program?
- Problem could be split into two parts: A and B. A is serial, B is parallel. On single CPU, A takes 50 minutes, B takes 250 minutes. How many CPUs do you need to solve the problem in 100 minutes (achieve 3x speed-up)?
- Prepare an example where 10x speed-up could be achieved by using 100 CPUs only.

<https://github.com/Svazars/parallel-programming/blob/main/hw/block1/1.4/readme.markdown>

Homework, mail

Task 1.4 Provide answers and explanation for all three problems

Embarrassingly parallel problems

Piece of advice

Such problems usually quite interesting and practically-oriented.

They do **not** require non-trivial coordination so we will not cover them in this course.

In many domains, most of "performance issues" are (almost) embarrassingly parallel.

There are plenty of

- easy-to-use
- straightforward
- safe
- stable
- performant

solutions to such problems. Just use them and get speed-up predicted by Amdahl's law.

If you go real concurrency, it will be **harder**.

Lecture plan

- 1 Motivation
- 2 Concurrency and parallelism
- 3 Scheduler
- 4 Threads and processes
- 5 Multitasking and threading models
- 6 Concurrent problems
 - Embarrassingly parallel problems and Amdahl's law
 - **Race condition**
 - Data race
 - Visibility
 - Deadlock
 - Priority inversion
- 7 Summary

Race condition

Example

```
public static void main(String... args) throws Exception {  
    Thread t1 = new Thread(() -> { System.out.println("Thread A"); });  
    Thread t2 = new Thread(() -> { System.out.println("Thread B"); });  
    t1.start(); t2.start();  
    t1.join(); t2.join();  
}
```

Race condition

Example

```
public static void main(String... args) throws Exception {  
    Thread t1 = new Thread(() -> { System.out.println("Thread A"); });  
    Thread t2 = new Thread(() -> { System.out.println("Thread B"); });  
    t1.start(); t2.start();  
    t1.join(); t2.join();  
}
```

Execution 1: Thread A Thread B

Execution 2: Thread B Thread A

Race condition

Key idea

- Every single operation in program is OK (properly synchronized, atomic)
- Program as a whole suffers from non-deterministic behaviour
- The only reason to this is different speed of execution

Race condition

Key idea

- Every single operation in program is OK (properly synchronized, atomic)
- Program as a whole suffers from non-deterministic behaviour
- The only reason to this is different speed of execution

<https://github.com/Svazars/parallel-programming/blob/main/hw/block1/1.5/readme.markdown>

Homework, mail

Task 1.5 Open <https://deadlockempire.github.io>, pass all levels up to "Confused counter", inclusive.

Race condition

Conclusion

Race condition

- at least 2 threads involved
- behaviour of system depends on sequence of events (e.g. timings)
- leads to non-deterministic results

Race condition

Conclusion

Race condition

- at least 2 threads involved
- behaviour of system depends on sequence of events (e.g. timings)
- leads to non-deterministic results

Really **suspicious**

- complicates analysis of algorithm (correctness, performance, resource utilization)
- may lead to rarely reproducible bugs
- may lead to random denial-of-service events

Race condition

Conclusion

Race condition

- at least 2 threads involved
- behaviour of system depends on sequence of events (e.g. timings)
- leads to non-deterministic results

Really **suspicious**

Race condition

Conclusion

Race condition

- at least 2 threads involved
- behaviour of system depends on sequence of events (e.g. timings)
- leads to non-deterministic results

Really **suspicious**

Not **necessarily** a problem

- Server counts number of incoming requests.
- Search engine crawls page graph using several workers. Many pages visited several times, deduplication makes result consistent.
- Torrent client downloads several chunks of a file simultaneously.

Race condition

Conclusion

Race condition

- at least 2 threads involved
- behaviour of system depends on sequence of events (e.g. timings)
- leads to non-deterministic results

Really **suspicious**

Not **necessarily** a problem

Race condition

Conclusion

Race condition

- at least 2 threads involved
- behaviour of system depends on sequence of events (e.g. timings)
- leads to non-deterministic results

Really **suspicious**

Not **necessarily** a problem

Main headache of our course:

- **Race condition may be a bug or intentional behaviour depending on programmer's intention**

In general, cannot be detected by static code analysis/dynamic instrumentation tool.

Question time

Question: Some tools detect race conditions in concurrent software. What is "false positive" detection of race condition?



Lecture plan

- 1 Motivation
- 2 Concurrency and parallelism
- 3 Scheduler
- 4 Threads and processes
- 5 Multitasking and threading models
- 6 Concurrent problems
 - Embarrassingly parallel problems and Amdahl's law
 - Race condition
 - **Data race**
 - Visibility
 - Deadlock
 - Priority inversion
- 7 Summary

Data race

Example 1

```
static volatile int x = 0;
public static void main(String... args) throws Exception {
    Thread t = new Thread(() -> { x++; });
    t.start();
    System.out.println(x);
    t.join();
}
```

Data race

Example 1

```
static volatile int x = 0;
public static void main(String... args) throws Exception {
    Thread t = new Thread(() -> { x++; });
    t.start();
    System.out.println(x);
    t.join();
}
```

Execution 1: x = 0

Execution 2: x = 1

Data race

Example 2

```
static volatile int x = 0;
public static void main(String... args) throws Exception {
    Thread t = new Thread(() -> { x++; });
    t.start();
    x++;
    System.out.println(x);
    t.join();
}
```

Data race

Example 2

```
static volatile int x = 0;
public static void main(String... args) throws Exception {
    Thread t = new Thread(() -> { x++; });
    t.start();
    x++;
    System.out.println(x);
    t.join();
}
```

Execution 1: x = 1

Execution 2: x = 2

Data race

Example 2.5

```
static volatile int x = 0;
public static void main(String... args) throws Exception {
    Thread t = new Thread(() -> { x++; });
    t.start();
    x++;
    t.join();
    System.out.println(x);
}
```

Data race

Example 2.5

```
static volatile int x = 0;
public static void main(String... args) throws Exception {
    Thread t = new Thread(() -> { x++; });
    t.start();
    x++;
    t.join();
    System.out.println(x);
}
```

Execution 1: x = 2

Data race

Example 2.5

```
static volatile int x = 0;
public static void main(String... args) throws Exception {
    Thread t = new Thread(() -> { x++; });
    t.start();
    x++;
    t.join();
    System.out.println(x);
}
```

Execution 1: x = 2

Execution 2: x = 1

Data race

Example 2.5

```
static volatile int x = 0;
public static void main(String... args) throws Exception {
    Thread t = new Thread(() -> { x++; });
    t.start();
    x++;
    t.join();
    System.out.println(x);
}
```

Execution 1: x = 2

Execution 2: x = 1

$x++ \Leftrightarrow \text{int tmp} = x; \text{tmp} = \text{tmp} + 1; x = \text{tmp}$

Data race

Key idea

Actually, formal definition exists and is language-specific. More on this in next lectures.

Data race:

- at least 2 threads
- at least one of threads is writing data
- operating on the same *memory location* (Lecture 9)
- *simultaneously* (Lecture 6)
- without *proper synchronization* (Lecture 10)

Any data race is race condition. Not every race condition is data race.

Data race

Compound data example

```
static volatile ArrayList<String> list = new ArrayList<>();
public static void main(String... args) throws Exception {
    Thread t1 = new Thread(() -> { list.add("x"); });
    Thread t2 = new Thread(() -> { list.add("y"); });
    t1.start(); t2.start();
    t1.join(); t2.join();
    for (String s : list) {
        System.out.println(s);
    }
}
```

Data race

Compound data example

```
static volatile ArrayList<String> list = new ArrayList<>();
public static void main(String... args) throws Exception {
    Thread t1 = new Thread(() -> { list.add("x"); });
    Thread t2 = new Thread(() -> { list.add("y"); });
    t1.start(); t2.start();
    t1.join(); t2.join();
    for (String s : list) {
        System.out.println(s);
    }
}
```

What is the size of list? 1 or 2?

Data race

Compound data example

```
static volatile ArrayList<String> list = new ArrayList<>();
public static void main(String... args) throws Exception {
    Thread t1 = new Thread(() -> { list.add("x"); });
    Thread t2 = new Thread(() -> { list.add("y"); });
    t1.start(); t2.start();
    t1.join(); t2.join();
    for (String s : list) {
        System.out.println(s);
    }
}
```

What is the size of list? 1 or 2?

Data race may lead to **inconsistent** state even if every thread executed only "valid" operations.

Data race

Conclusion

Data race is a specific variation of race condition

- concurrent and not properly synchronized
- write access
- to shared data

Always **problematic**

- inconsistent shared state
- unexpected/impossible computation results
- forbidden by language implementation

Could be formalized and avoided

- Strict coding policy (e.g. enforced by linter/compiler)
- Static analysis of source code
- Static analysis of execution traces
- Dynamic instrumenting race finders

Question time

Question: Some tools detect data races in concurrent software. Why do we still have systems with data races?



Lecture plan

- 1 Motivation
- 2 Concurrency and parallelism
- 3 Scheduler
- 4 Threads and processes
- 5 Multitasking and threading models
- 6 Concurrent problems
 - Embarrassingly parallel problems and Amdahl's law
 - Race condition
 - Data race
 - **Visibility**
 - Deadlock
 - Priority inversion
- 7 Summary

Visibility

Introduction

It is one of the most subtle notions in concurrency.

Visibility

Introduction

It is one of the most subtle notions in concurrency.

For now, we should expect that

- compiler could aggressively reorder/eliminate field operations
- threads may see stale values, not the "newest" values written by other threads

unless there is "synchronization point" between two threads

Visibility

Introduction

It is one of the most subtle notions in concurrency.

For now, we should expect that

- compiler could aggressively reorder/eliminate field operations
- threads may see stale values, not the "newest" values written by other threads

unless there is "synchronization point" between two threads

- `Thread.start`
- `Thread.join`

Visibility

Incorrect: message passing via plain fields

```
static boolean jobDone = false;
public static void main(String... args) throws Exception {
    Thread t = new Thread(() -> { jobDone = true; });
    t.start();
    while (jobDone == false) { /* loop */ }
    t.join();
}
```

Visibility

Incorrect: message passing via plain fields

```
static boolean jobDone = false;
public static void main(String... args) throws Exception {
    Thread t = new Thread(() -> { jobDone = true; });
    t.start();
    while (jobDone == false) { /* loop */ }
    t.join();
}
```

May hang because:

- compiler optimization: if (!jobDone) while(true);
- stale value, jobDone remains false in main thread forever

Lecture plan

- 1 Motivation
- 2 Concurrency and parallelism
- 3 Scheduler
- 4 Threads and processes
- 5 Multitasking and threading models
- 6 Concurrent problems
 - Embarrassingly parallel problems and Amdahl's law
 - Race condition
 - Data race
 - Visibility
 - **Deadlock**
 - Priority inversion
- 7 Summary

Blocking methods

Wait-for graph

Blocking method: execution of current thread is *suspended* until some condition is met.

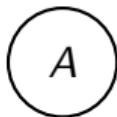
```
Thread A = new Thread(() -> {
    Thread B = new Thread(() -> { Thread.sleep(10_000); });
    Thread C = new Thread(() -> { B.join(); Thread.sleep(10_000); });
    B.start(); C.start(); B.join(); C.join()
}); A.start(); A.join();
```

Blocking methods

Wait-for graph

Blocking method: execution of current thread is *suspended* until some condition is met.

```
Thread A = new Thread(() -> {
    Thread B = new Thread(() -> { Thread.sleep(10_000); });
    Thread C = new Thread(() -> { B.join(); Thread.sleep(10_000); });
    B.start(); C.start(); B.join(); C.join()
}); A.start(); A.join();
```

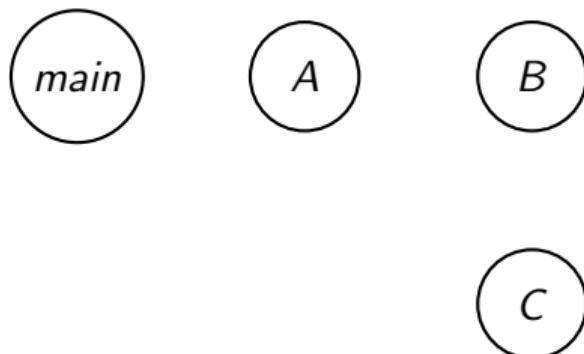


Blocking methods

Wait-for graph

Blocking method: execution of current thread is *suspended* until some condition is met.

```
Thread A = new Thread(() -> {
    Thread B = new Thread(() -> { Thread.sleep(10_000); });
    Thread C = new Thread(() -> { B.join(); Thread.sleep(10_000); });
    B.start(); C.start(); B.join(); C.join()
}); A.start(); A.join();
```

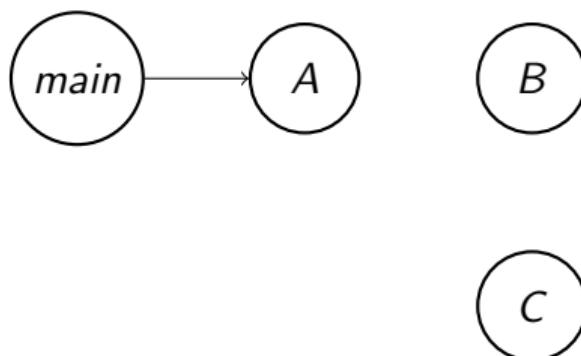


Blocking methods

Wait-for graph

Blocking method: execution of current thread is *suspended* until some condition is met.

```
Thread A = new Thread(() -> {
    Thread B = new Thread(() -> { Thread.sleep(10_000); });
    Thread C = new Thread(() -> { B.join(); Thread.sleep(10_000); });
    B.start(); C.start(); B.join(); C.join()
}); A.start(); A.join();
```

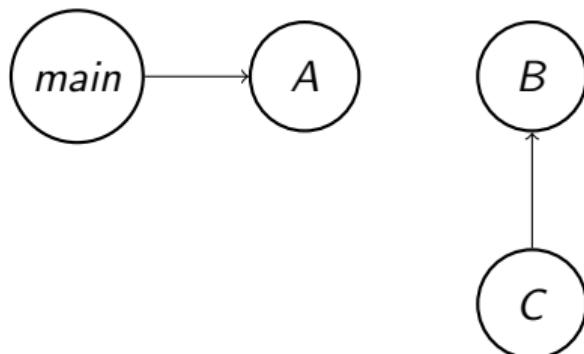


Blocking methods

Wait-for graph

Blocking method: execution of current thread is *suspended* until some condition is met.

```
Thread A = new Thread(() -> {
    Thread B = new Thread(() -> { Thread.sleep(10_000); });
    Thread C = new Thread(() -> { B.join(); Thread.sleep(10_000); });
    B.start(); C.start(); B.join(); C.join()
}); A.start(); A.join();
```

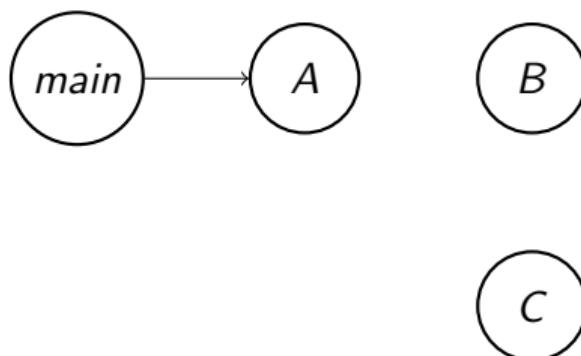


Blocking methods

Wait-for graph

Blocking method: execution of current thread is *suspended* until some condition is met.

```
Thread A = new Thread(() -> {
    Thread B = new Thread(() -> { Thread.sleep(10_000); });
    Thread C = new Thread(() -> { B.join(); Thread.sleep(10_000); });
    B.start(); C.start(); B.join(); C.join()
}); A.start(); A.join();
```



Blocking methods

Deadlock

Deadlock – cycle in wait-for graph.

Blocking methods

Deadlock

Deadlock – cycle in wait-for graph.

Trivial single-threaded deadlock:

Blocking methods

Deadlock

Deadlock – cycle in wait-for graph.

Trivial single-threaded deadlock:

```
Thread.currentThread().join();
```

Blocking methods

Deadlock

Deadlock – cycle in wait-for graph.

Trivial single-threaded deadlock:

```
Thread.currentThread().join();
```

Classic two-thread deadlock:

```
static volatile Runnable lambda = null;
public static void main(String... args) throws Exception {
    Thread A = new Thread(() -> { lambda.run(); });
    Thread B = new Thread(() -> { A.join(); });
    lambda = () -> { B.join(); };
    A.start(); B.start();
    A.join(); B.join();
}
```

Blocking methods

Deadlock visualisation

```
java Sample &
PID="$!" && sleep 1
jstack -l $PID
```

Blocking methods

Deadlock visualisation

```
java Sample &  
PID="$!" && sleep 1  
jstack -l $PID
```

Output:

```
"main" #1 prio=5 os_prio=0 cpu=38,96ms elapsed=1,25s tid=0x00007fdcc0017000 nice=0  
java.lang.Thread.State: WAITING (on object monitor)  
  at java.lang.Object.wait(java.base@14.0.1/Native Method)  
    - waiting on <0x0000000095148930> (a java.lang.Thread)  
    ...  
  at Sample.main(Sample.java:10)  
  ...
```

Blocking methods

Deadlock detection

- If API has at least one blocking method – extreme care required to avoid deadlocks
- If you do not know in which thread your code will be executed – extreme care required to avoid deadlocks
- If you can not control execution (inheritance, virtual methods, function pointers) – extreme care required to avoid deadlocks
- Design of any concurrent system should start with preparing tools for debugging and monitoring (observability API)

Blocking methods

Deadlock detection

- If API has at least one blocking method – extreme care required to avoid deadlocks
- If you do not know in which thread your code will be executed – extreme care required to avoid deadlocks
- If you can not control execution (inheritance, virtual methods, function pointers) – extreme care required to avoid deadlocks
- Design of any concurrent system should start with preparing tools for debugging and monitoring (observability API)

<https://github.com/Svazars/parallel-programming/blob/main/hw/block1/1.6/readme.markdown>

Homework, mail

Task 1.6 Run jstack on all deadlock samples from this lecture.

Question time

Question: Object-oriented languages love to "hide" implementation details using abstractions (inheritance, virtual methods, function pointers, interfaces). How would I know that user of my library/module will not call blocking method and introduce deadlock in my system?



Lecture plan

- 1 Motivation
- 2 Concurrency and parallelism
- 3 Scheduler
- 4 Threads and processes
- 5 Multitasking and threading models
- 6 Concurrent problems
 - Embarrassingly parallel problems and Amdahl's law
 - Race condition
 - Data race
 - Visibility
 - Deadlock
 - Priority inversion
- 7 Summary

Blocking methods

Priority inversion

```
public static void main(String... args) {  
    Thread A = new Thread(() -> { do1(); B = startThread(); do2(); B.join(); });  
    A.start(); doCriticalWork(); A.join();  
}
```

main waitsFor A, A waitsFor B.

Progress of main determined by progress of B.

"Soft" version of deadlock (depends-on graph).

- Some Operation Systems **do** have special support to remedy priority inversion problems
- Many Virtual Machines, concurrent libraries, multi-threaded frameworks **do not**

Blocking methods

Priority inversion

```
public static void main(String... args) {  
    Thread A = new Thread(() -> { do1(); B = startThread(); do2(); B.join(); });  
    A.start(); doCriticalWork(); A.join();  
}
```

main waitsFor A, A waitsFor B.

Progress of main determined by progress of B.

"Soft" version of deadlock (depends-on graph).

- Some Operation Systems **do** have special support to remedy priority inversion problems
- Many Virtual Machines, concurrent libraries, multi-threaded frameworks **do not**

If you launch rovers on Mars, be ready to debug them¹³.

¹³<https://www.cs.cornell.edu/courses/cs614/1999sp/papers/pathfinder.html>

Lecture plan

- 1 Motivation
- 2 Concurrency and parallelism
- 3 Scheduler
- 4 Threads and processes
- 5 Multitasking and threading models
- 6 Concurrent problems
 - Embarrassingly parallel problems and Amdahl's law
 - Race condition
 - Data race
 - Visibility
 - Deadlock
 - Priority inversion
- 7 Summary

Summary

- Agents with different speed could communicate with each other via shared memory
- Parallel and concurrent execution could look similar and could happen in the same system
 - Concurrency: tasks may be interrupted in pre-defined places or arbitrary
 - Parallel: independent tasks may be executed simultaneously on different cores
- Threads are parts of OS processes and are minimal unit of work for scheduler
- There are different threading models: 1:1, N:1, N:M
- Interleaving N:1 is useful yet simplified model of concurrent execution
- The perfect scenario: problem could be divided into many independent parts with almost zero coordination overheads
- Amdahl's law fundamentally limits possible speed-up of tasks with sequential parts
- Whenever you coordinate threads, you encounter non-determinism, race conditions, data races, visibility issues, deadlocks, priority inversion

Summary: homework

Lecture 1, Tasks 1.*: <https://github.com/Svazars/parallel-programming/blob/main/hw/block1>