Introduction to Concurrent Programming

Lecture 1 of TDA384/DIT391

Principles of Concurrent Programming

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Today’s menu

- A motivating example
- Why concurrency?
- Basic terminology and abstractions
- Java threads
- Traces

A Motivating Example

As simple as counting to two

We illustrate the **challenges** introduced by concurrent programming on a simple example: a counter modeled by a Java class

- First, we write a traditional, sequential version

- Then, we introduce concurrency and…run into **trouble**!

Sequential counter

```
public class Counter {
  private int counter = 0;

  // increment counter by one
  public void run() {
     int cnt = counter;
     counter = cnt + 1;
  }

  // current value of counter
  public int counter() {
     return counter;
  }
}
```

```
public class SequentialCount {
  public static
  void main(String[] args) {
      Counter counter = new Counter();
      counter.run(); // increment once
      counter.run(); // increment
twice
      // print final value of counter
      System.out.println(
          counter.counter());
  }
}
```

- What is printed by running: `java SequentialCount`?
- May the printed value change in different reruns?

Modeling sequential computation

```
5  public void run() {
6      int cnt = counter; ●
7      counter = cnt + 1; ●
8  }                      ●
```

```
● counter.run(); // first call: steps 1-3
● counter.run(); // second call: steps 4-6
```

#	LOCAL STATE		OBJECT STATE
1	pc: 6	cnt: ⊥	counter: 0
2	pc: 7	cnt: 0	counter: 0
3	pc: 8	cnt: 0	counter: 1
4	pc: 6	cnt: ⊥	counter: 1
5	pc: 7	cnt: 1	counter: 1
6	pc: 8	cnt: 1	counter: 2
7	done		counter: **2**

Adding concurrency

Now, we revisit the example by introducing concurrency:

Each of the two calls to method `run` can be executed in parallel

- In Java, this is achieved by using threads
- Do not worry about the details of the syntax for now, we will explain it later

The idea is just that:

- There are two independent execution units (threads) `t` and `u`
- Each execution unit executes `run` on the same `counter` object
- We have no control over the order of execution of `t` and `u`

Concurrent counter

```
public class CCounter
    extends Counter
    implements Runnable
{
    // threads
    // will execute
    // run()
}
```

```
public class ConcurrentCount {
  public static void main(String[] args) {
     CCounter counter = new CCounter();
     // threads t and u, sharing counter
     Thread t = new Thread(counter);
     Thread u = new Thread(counter);
     t.start(); // increment once
     u.start(); // increment twice
     try { // wait for t and u to terminate
       t.join(); u.join();
     } catch (InterruptedException e) {
       System.out.println("Interrupted!");
     } // print final value of counter
     System.out.println(counter.counter());
} }
```

- What is printed by running: `java ConcurrentCount`?
- May the printed value change in different reruns?

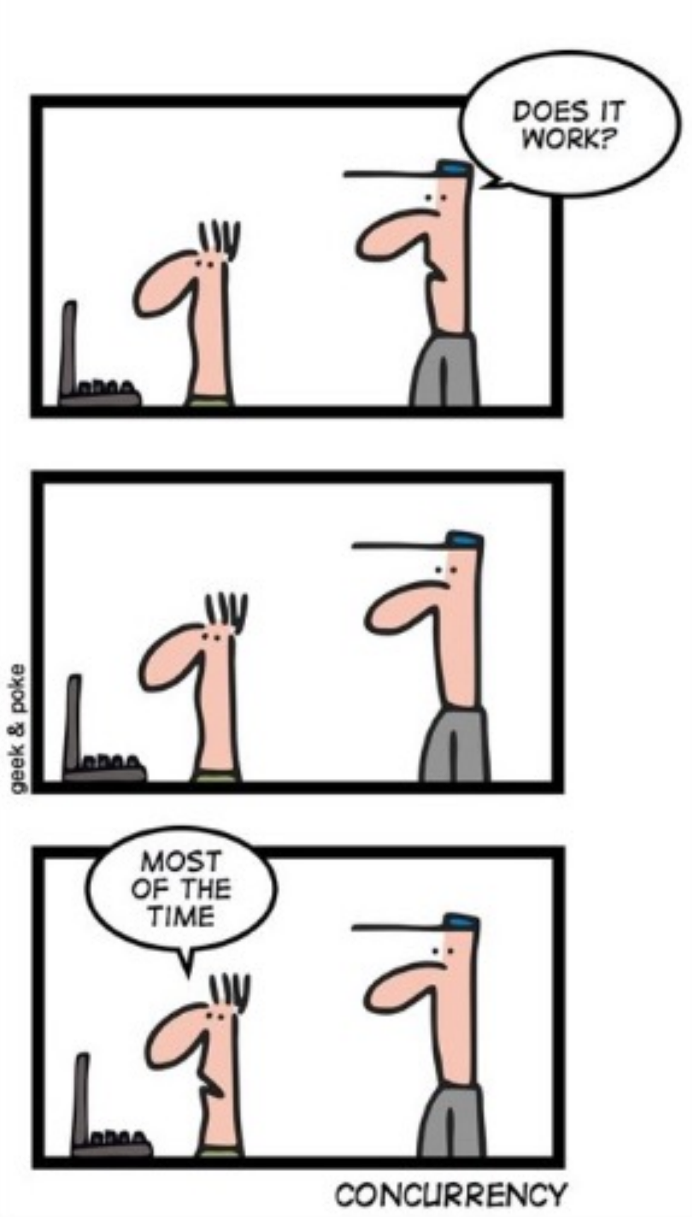
What?!

```
$ javac Counter.java CCounter.java ConcurrentCount.java
$ java ConcurrentCount.java
2
$ java ConcurrentCount.java
2
...
$ java ConcurrentCount.java
1
$ java ConcurrentCount.java
2
```

The concurrent version of counter occasionally prints 1 instead of the expected 2

- It seems to do so unpredictably

Welcome to concurrent programming!


DOES IT WORK?
MOST OF THE TIME
geek & poke
CONCURRENCY

Why concurrency?

Reasons for using concurrency

Why do we need concurrent programming in the first place?

- **Abstraction:**
  - Separating different tasks, without worrying about when to execute them (Ex: download files from two different websites)
- **Responsiveness:**
  - Providing a responsive user interface, with different tasks executing independently (Ex: browse the slides while downloading your email)
- **Performance:**
  - Splitting complex tasks in multiple units, and assign each unit to a different processor (Ex: compute all prime numbers up to 1 billion)

Concurrency vs. parallelism

Principles of concurrent programming

vs.

Principer för parallell programmering

Huh?

Concurrency vs. parallelism

We will mostly use concurrency and parallelism as synonyms

However, they refer to similar but different concepts:

- Concurrency: nondeterministic composition of independently executing units (logical parallelism)
- Parallelism: efficient execution of fractions of a complex task on multiple processing units (physical parallelism)

- You can have concurrency without physical parallelism: operating systems running on single-processor single-core systems
- Parallelism is mainly about speeding up computations by taking advantage of redundant hardware

Concurrency vs. parallelism

Ideal situation

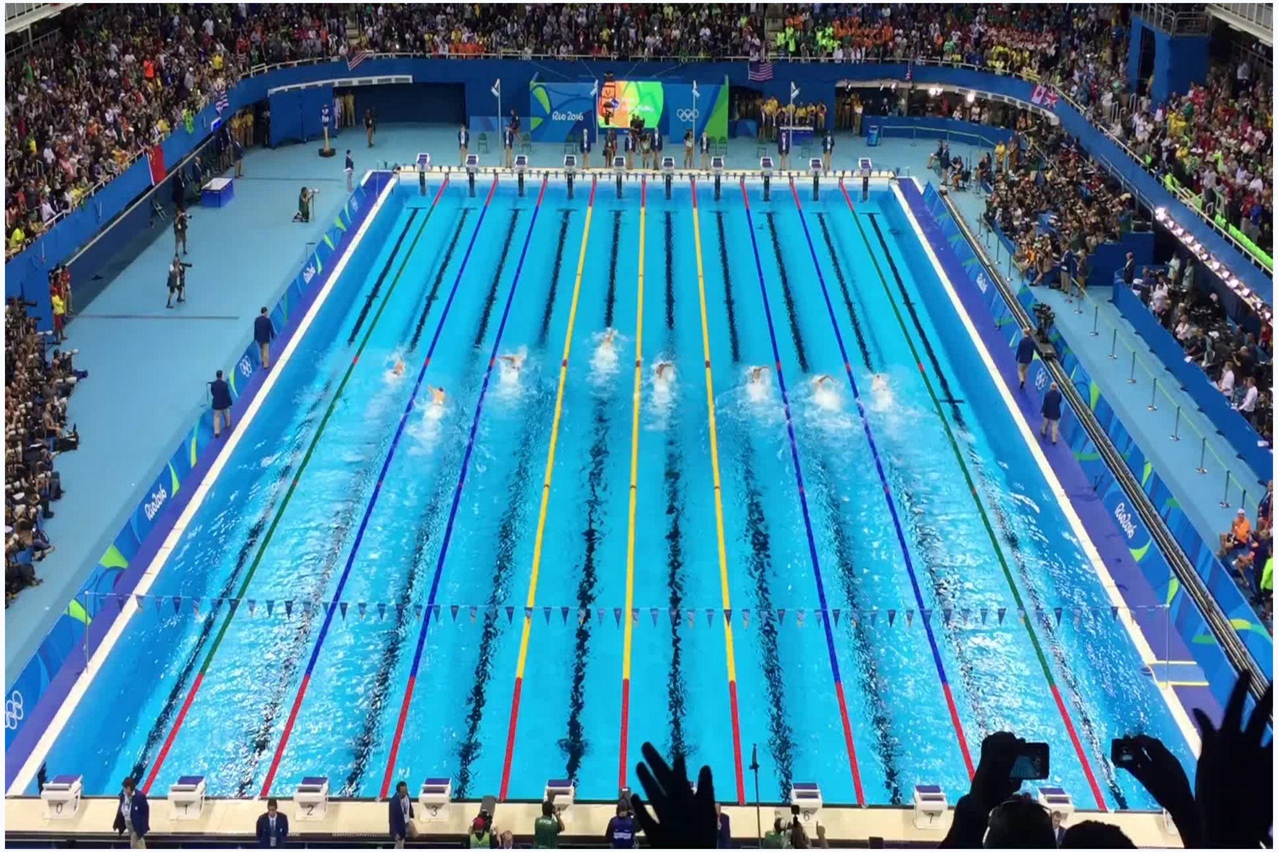


Photo: Summer Olympics 2016, Sander van Ginkel.

Concurrency vs. parallelism

More common situation

Photos: World Cup Nordic ’07, Tomoyoshi Noguchi – Vasaloppet ’06, Steven Hale.

Concurrency vs. parallelism

Real world situation

Photo: Daniel Mott 2009

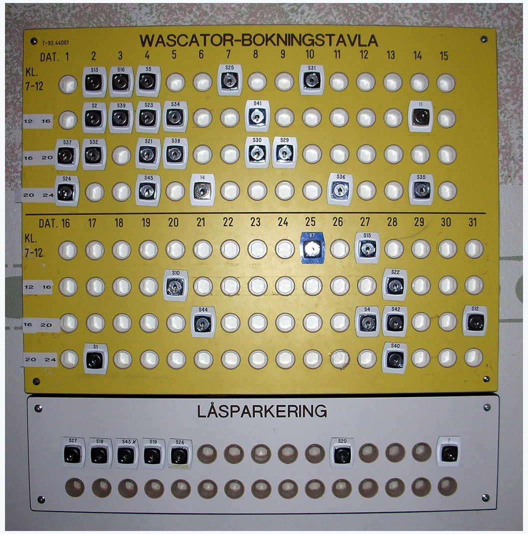


Photo: Wolfgangus Mozart 2010

Challenges:

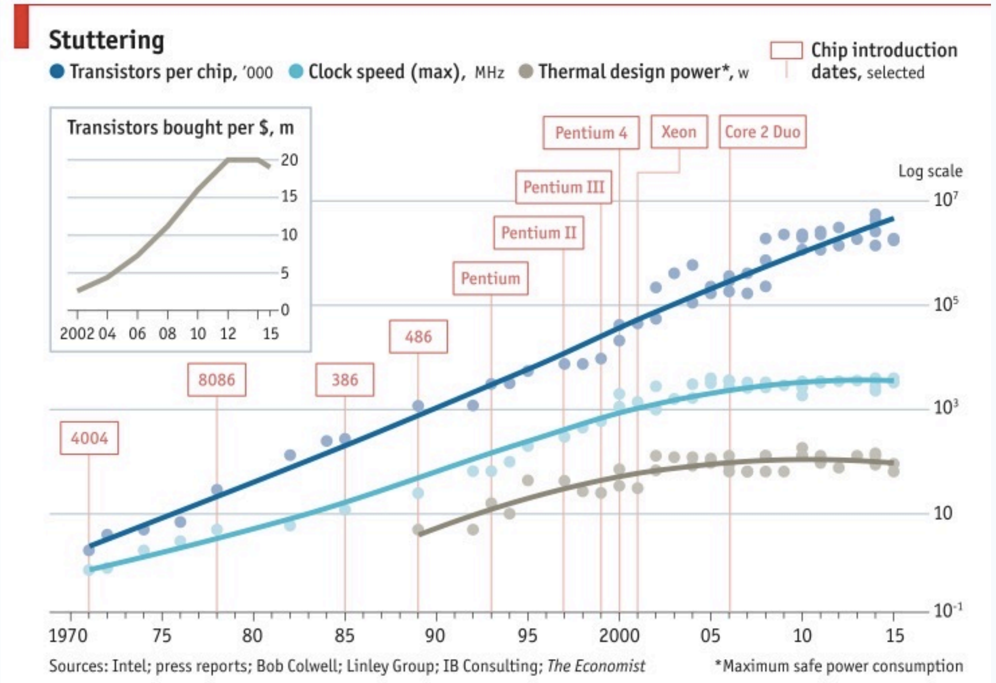
- *Concurrency:* Everyone gets to do their laundry (**fairness**)
  Machines are operated by at most one user (**mutual exclusion**)
- *Parallelism:* Distribute load evenly over machines/rooms (**load balancing**)

Solutions: schedules, locks, signs/indicators…

Moore's law and its end (?)

The spectacular advance of computing in the last 60+ years has been driven by Moore’s law (1965)

1975: The density of transistors in integrated circuits doubles approximately every 2 years



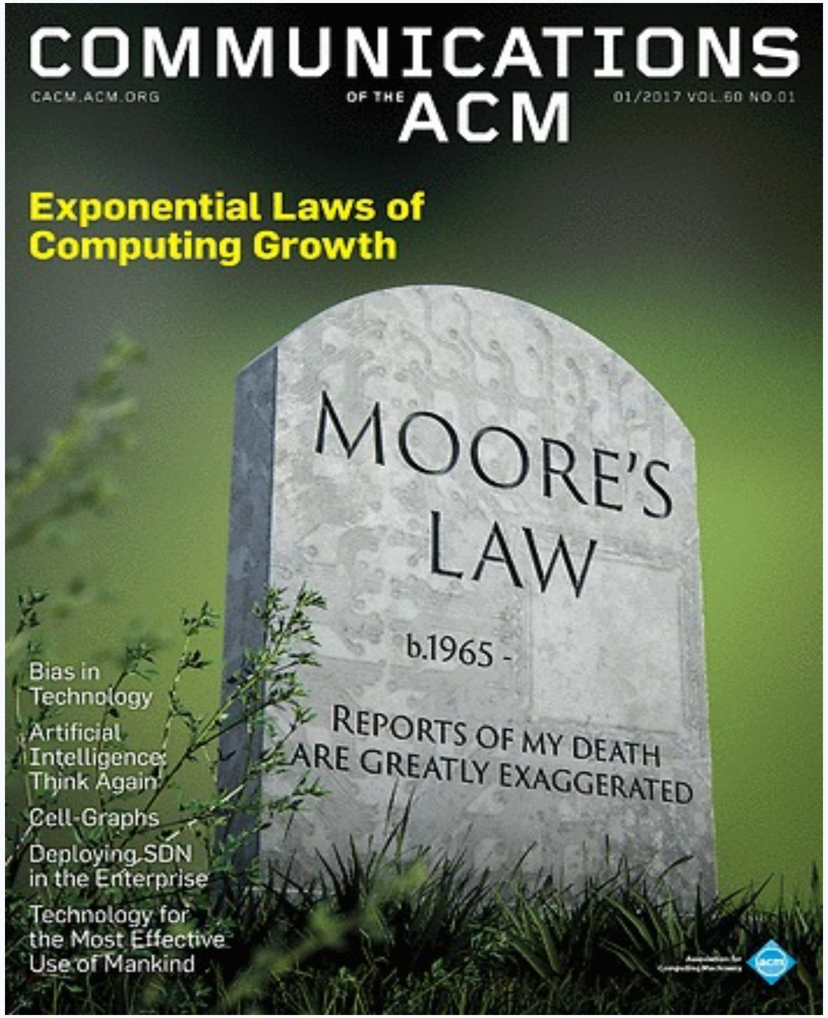
Stuttering

Sources: Intel; press reports; Bob Colwell; Linley Group; IB Consulting; *The Economist*

*Maximum safe power consumption

Later updated:
Doubling every
18 months
(instead of 2 years)

Moore's Law in January 2017



COMMUNICATIONS OF THE ACM

CACM.ACM.ORG

01/2017 VOL.60 NO.01

Exponential Laws of Computing Growth

Bias in Technology

Artificial Intelligence: Think Again

Cell-Graphs

Deploying SDN in the Enterprise

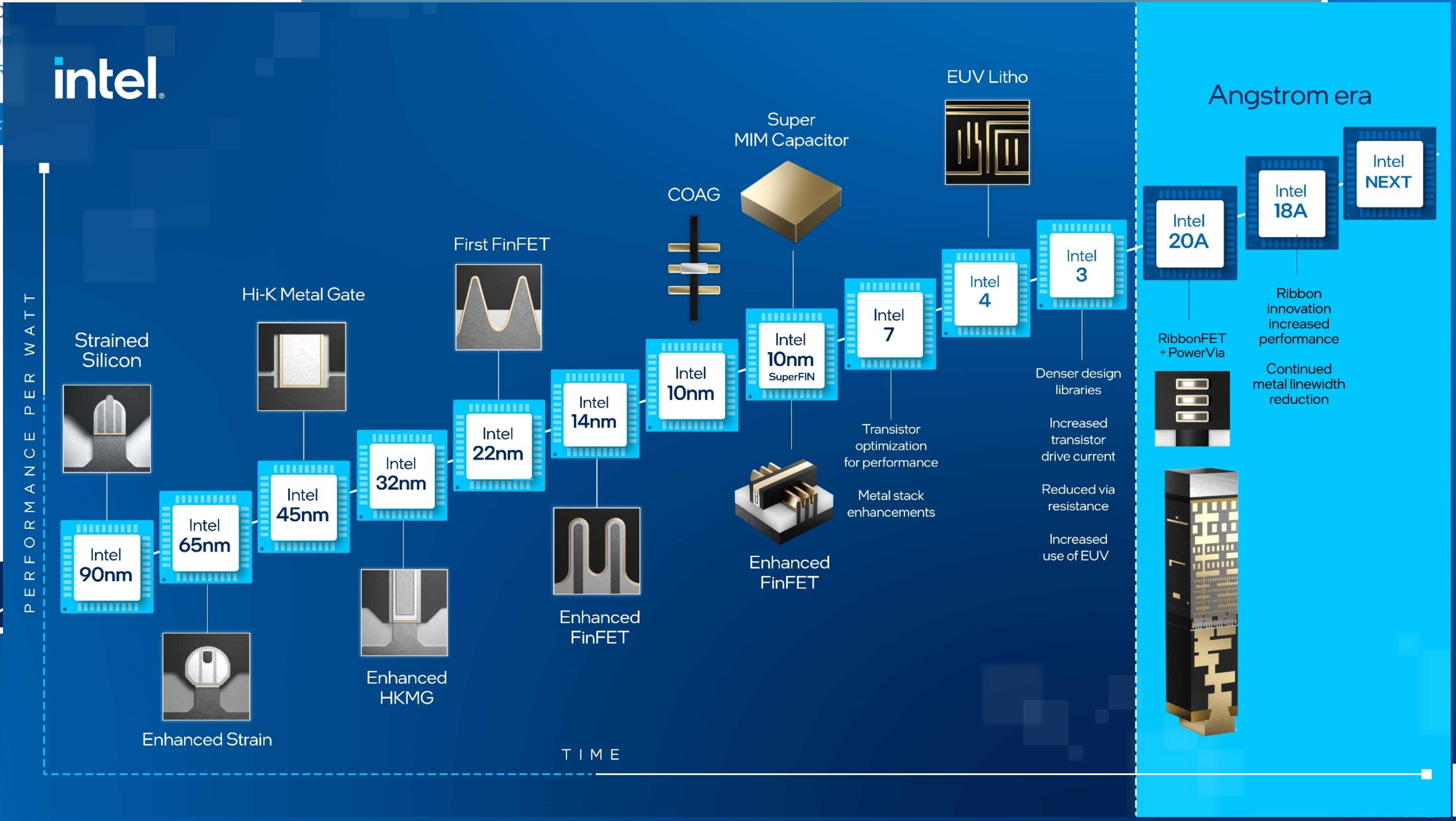
Technology for the Most Effective Use of Mankind

Opinion

- February 16, 20
- Download a PD
- Contact Intel PR

More Manufac

1970



intel.

Strained Silicon

Hi-K Metal Gate

First FinFET

COAG

Super MIM Capacitor

EUV Litho

Angstrom era

Intel 90nm

Intel 65nm

Intel 45nm

Intel 32nm

Intel 22nm

Intel 14nm

Intel 10nm

Intel 10nm SuperFIN

Intel 7

Intel 4

Intel 3

Intel 20A

Intel 18A

Intel NEXT

Enhanced Strain

Enhanced HKMG

Enhanced FinFET

Enhanced FinFET

Transistor optimization for performance

Metal stack enhancements

Denser design libraries

Increased transistor drive current

Reduced via resistance

Increased use of EUV

RibbonFET + PowerVia

Ribbon innovation increased performance

Continued metal linewidth reduction

Concurrency everywhere

Physical restrictions force to change from increasing processing speed to having multiple processing having a major impact on the practice of programming:

- **Before:** CPU speed increases without significant architectural changes
  - Concurrent programming was a niche skill (for operating systems, databases, high-performance computing)
  - Program as usual and wait for your program to run faster
- **Now:** CPU speed remains the same, but number of cores increases
  - Concurrent programming is pervasive
  - Program with concurrency in mind, otherwise your programs remain slow

Very different systems all require concurrent programming:

- desktop PCs,
- smart phones,
- video-games consoles,
- embedded systems,
- the Raspberry Pi,
- cloud computing, …

Amdahl's law: Concurrency is no free lunch

We have n processors that can run in parallel

How much speedup can we achieve?

$$\boldsymbol{speedup} = \frac{\boldsymbol{sequential\ execution\ time}}{\boldsymbol{parallel\ execution\ time}}$$

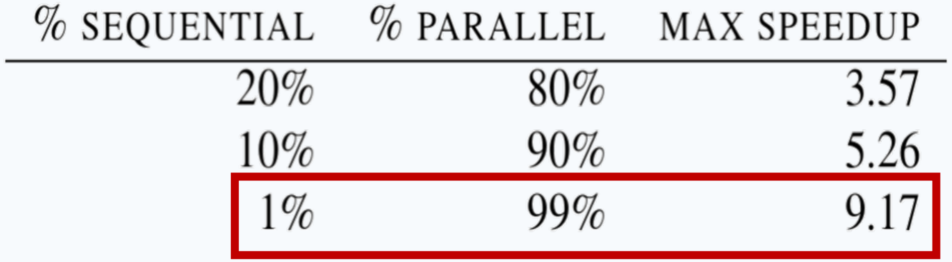
Amdahl’s law shows that the impact of introducing parallelism is limited by the fraction p of a program that can be parallelized:

$$\boldsymbol{maximum\ speedup} = \frac{\mathbf{1}}{\underbrace{(\mathbf{1} - \boldsymbol{p})}_{\text{sequential part}} + \underbrace{\boldsymbol{p}/\boldsymbol{n}}_{\text{parallel part}}}$$

Amdahl's law: Examples

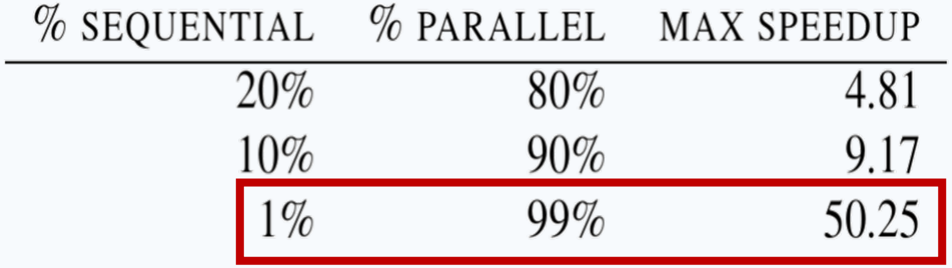
$$\boldsymbol{maximum\ speedup} = \frac{\mathbf{1}}{(\mathbf{1} - \boldsymbol{p}) + \boldsymbol{p}/\boldsymbol{n}}$$

With n=10 processors, how close can we get to a 10x speedup?



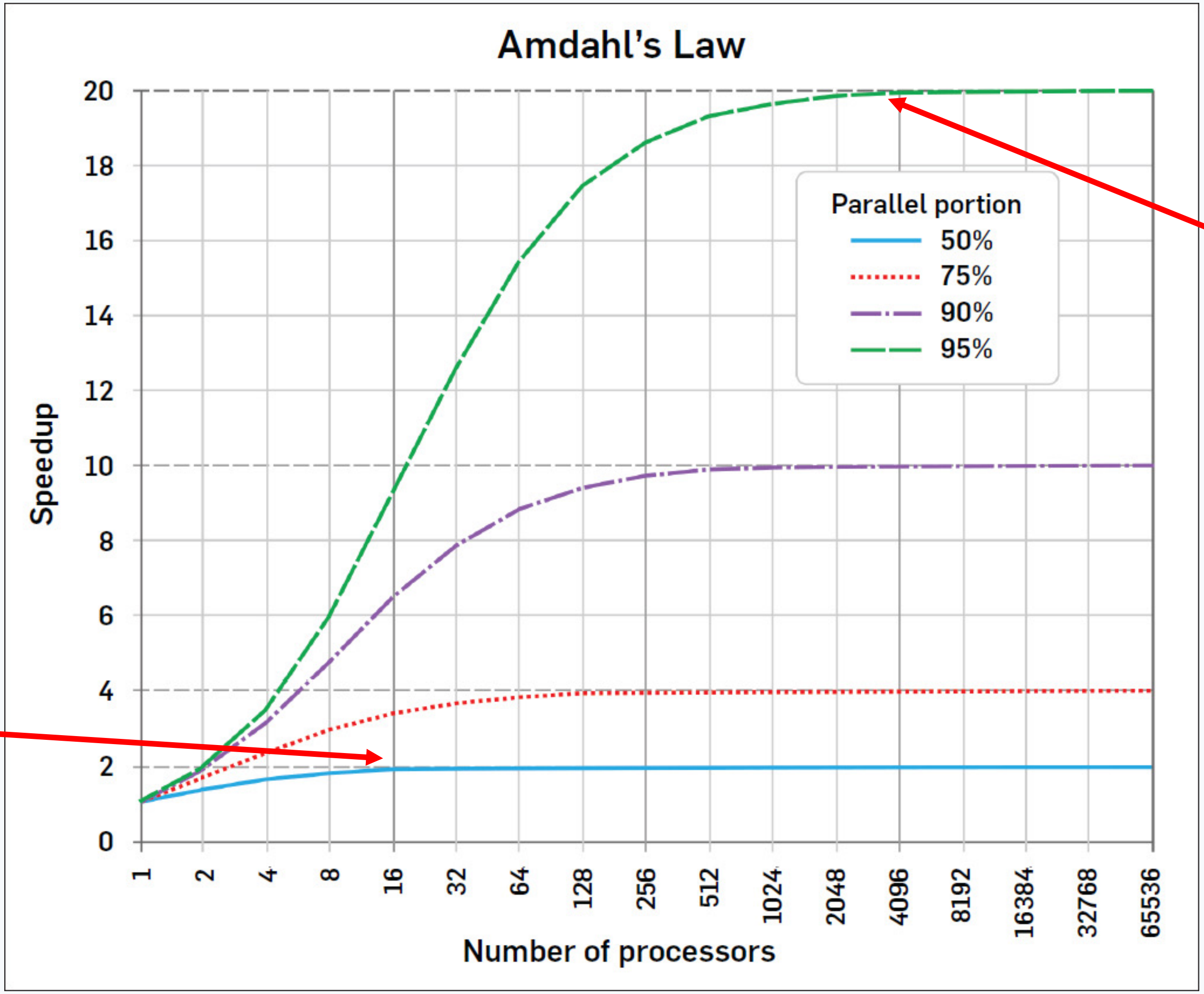
% SEQUENTIAL	% PARALLEL	MAX SPEEDUP
20%	80%	3.57
10%	90%	5.26
1%	99%	9.17

With n=100 processors, how close can we get to a 100x speedup?



% SEQUENTIAL	% PARALLEL	MAX SPEEDUP
20%	80%	4.81
10%	90%	9.17
1%	99%	50.25

Amdahl's law: Examples



95% parallelism:
Speedup up to 4096
processors
(uselss to add more)

50% parallelism:
Adding more than
16 processors is
useless

Source: Communications of the ACM, Dec. 2017

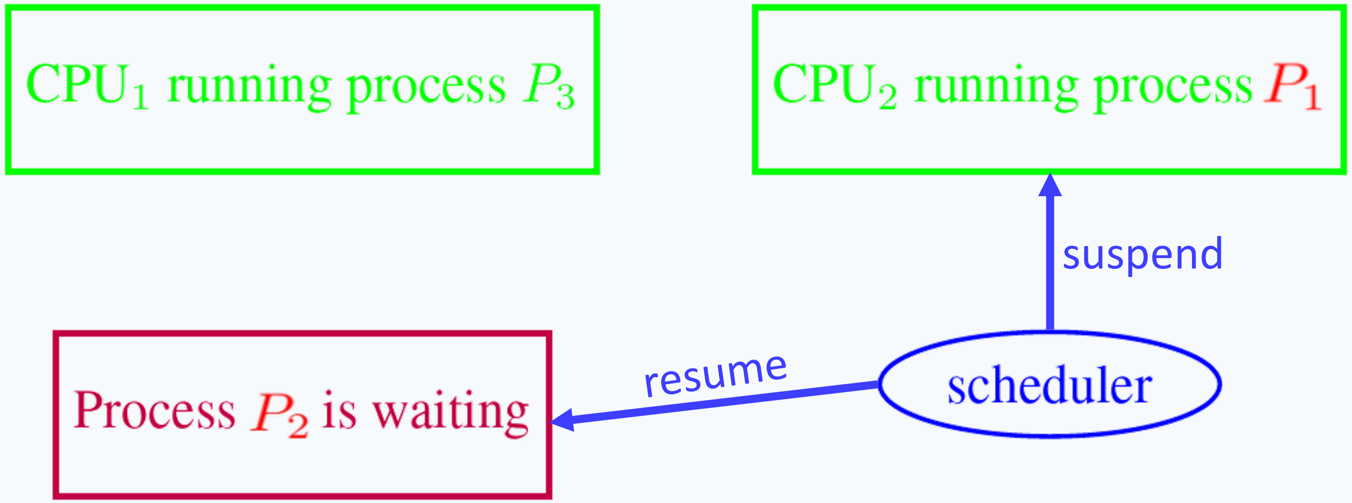
Basic terminology and abstractions

Processes

A process is an independent unit of execution – the abstraction of a running sequential program:

- identifier
- program counter (PC)
- memory space

The runtime/operating system schedules processes for execution on the available processors:



CPU$_1$ running process P_3

CPU$_2$ running process P_1

suspend

scheduler

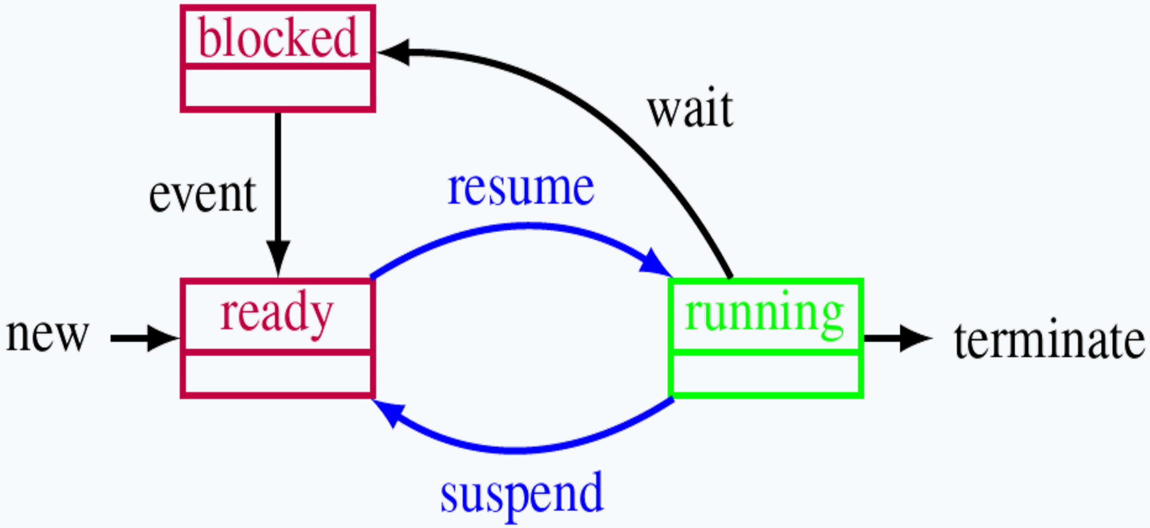
resume

Process P_2 is waiting

Process states

The scheduler is the system unit in charge of setting process states:

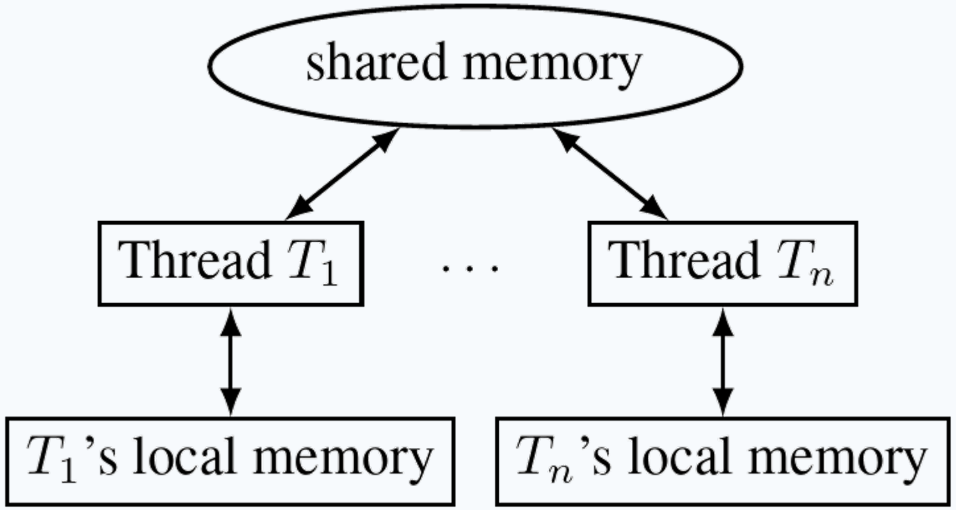
Ready:	ready to be executed, but not allocated to any CPU
Blocked:	waiting for an event to happen
Running:	running on some CPU



Threads

A thread is a lightweight process – an independent unit of execution in the same program space:

- identifier
- program counter (PC)
- memory
  - local memory, separate for each thread
  - global memory, shared with other threads



In practice, the difference between processes and threads is fuzzy and implementation dependent. In our course:

Processes: executing units that do **not** share memory (in Erlang)

Threads: executing units that share memory (in Java)

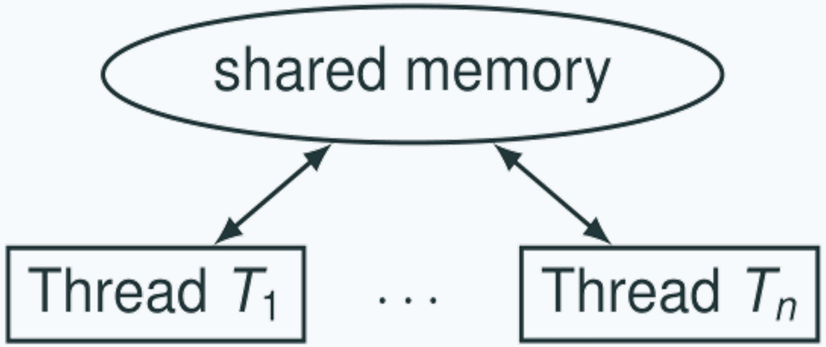
Shared memory vs. message passing

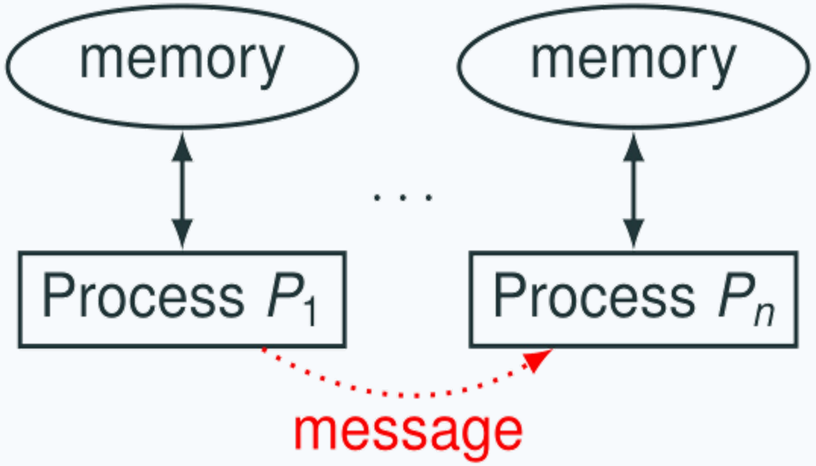
Shared memory models:

- communication by writing to shared memory
- e.g., multi-core systems

Distributed memory models:

- communication by message passing
- e.g., distributed systems



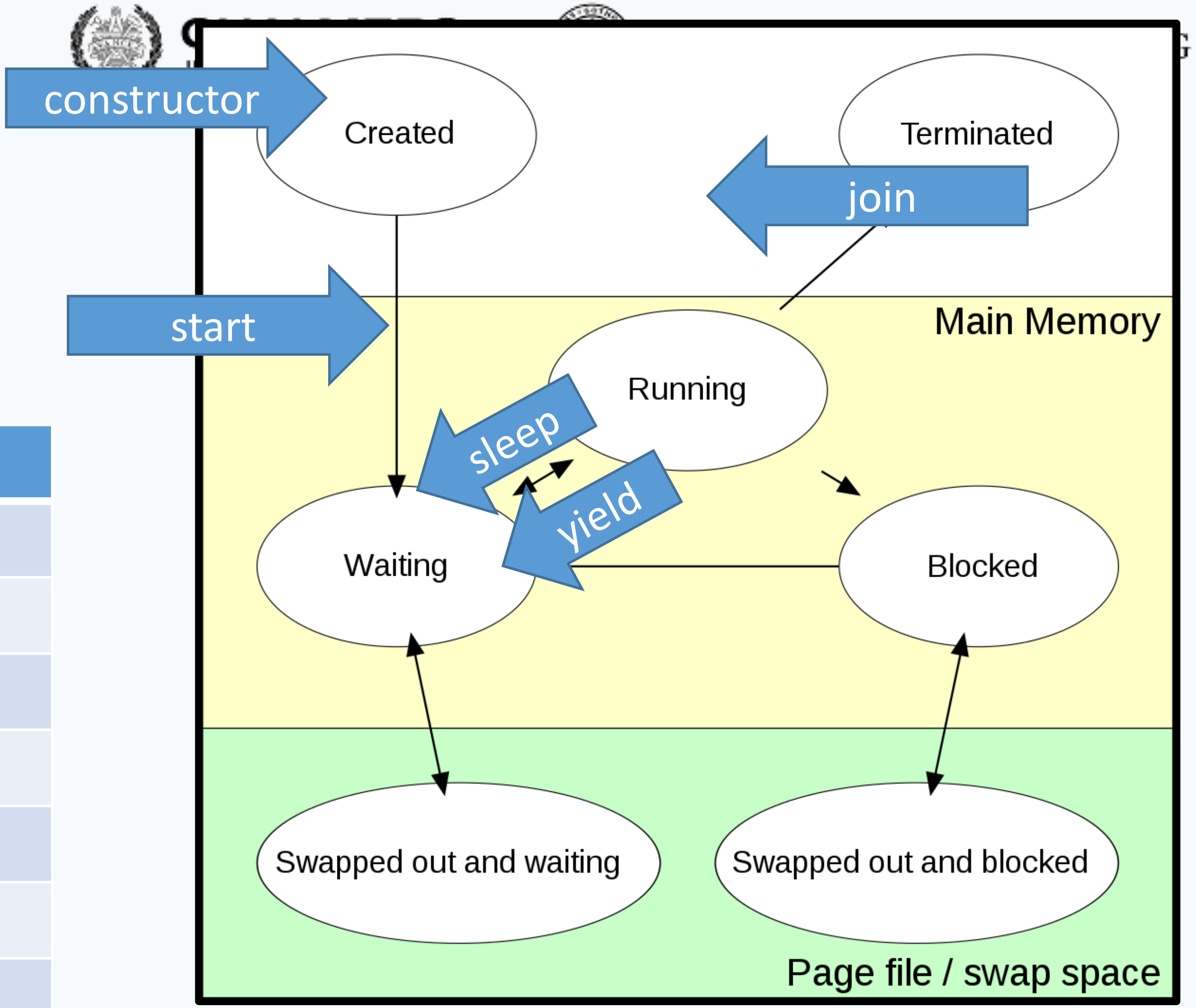


Java threads

Creating Threads

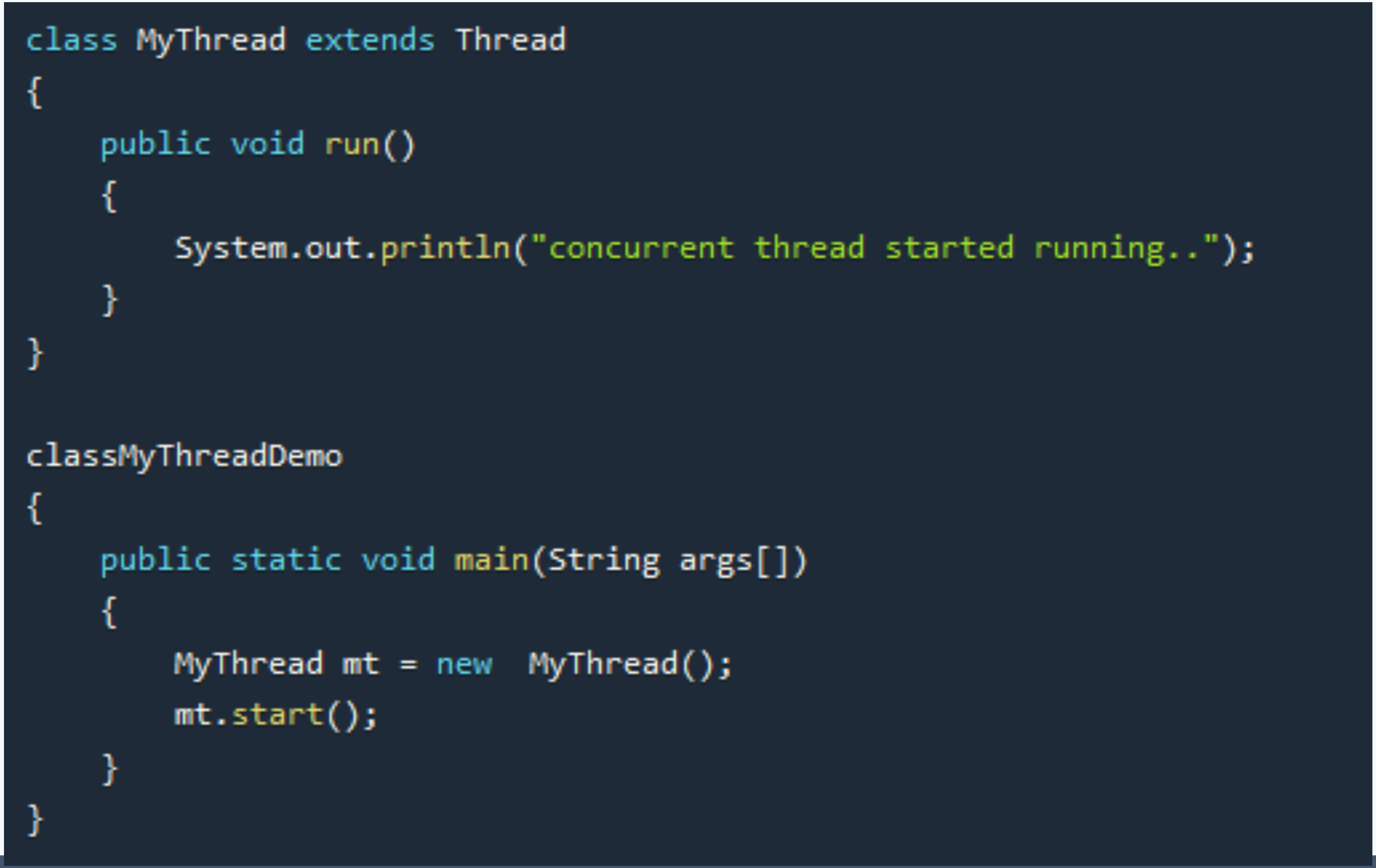
- What does a thread need to do?

Method	
start()	Start a thread by calling run() method
run()	Entry point for a thread
join()	Wait for a thread to end
isAlive()	Checks if thread is still running or not
setName()	
getName()	
getPriority()	



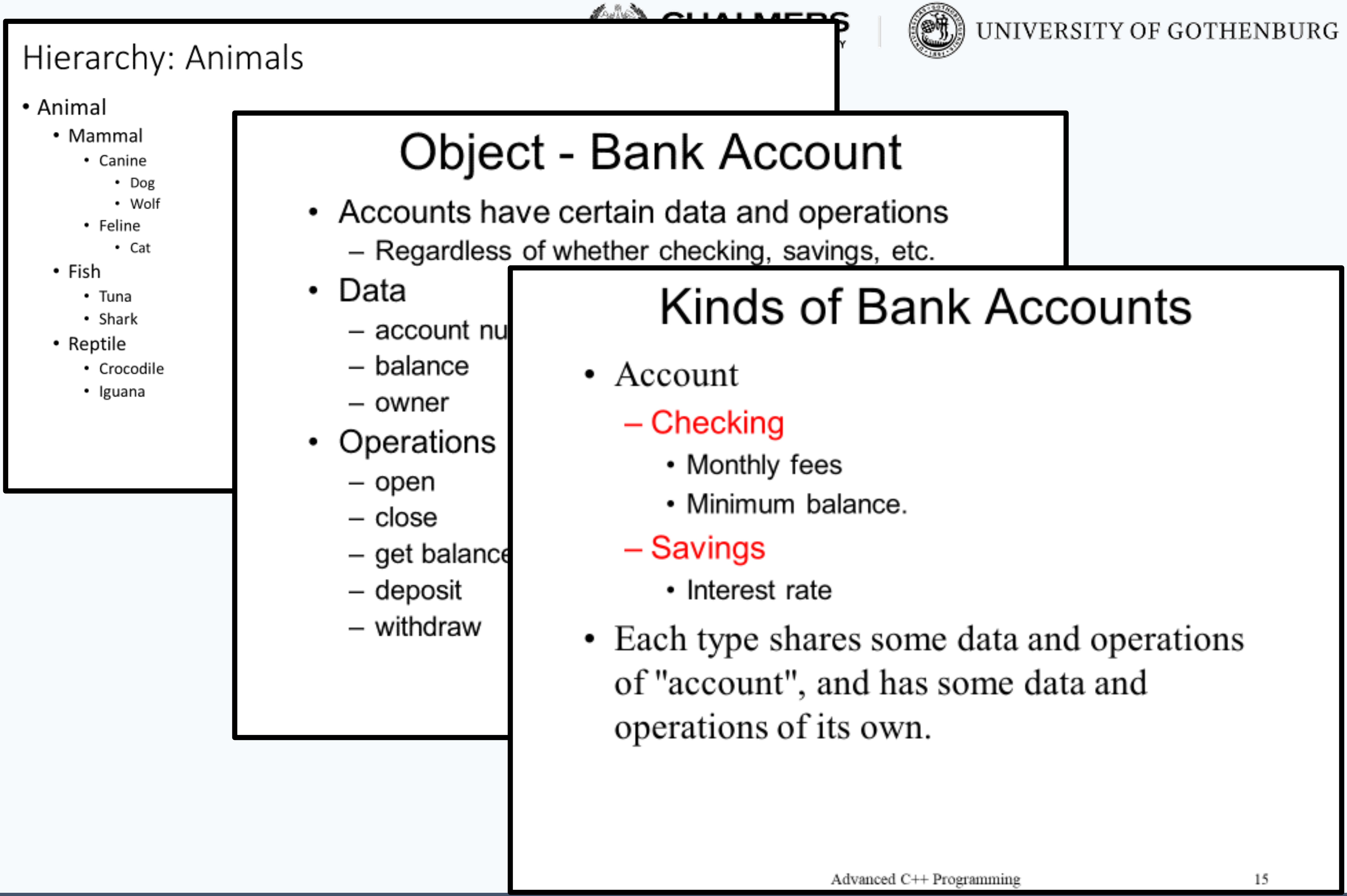
https://en.wikipedia.org/wiki/Process_state

Extend Thread



```
class MyThread extends Thread
{
    public void run()
    {
        System.out.println("concurrent thread started running..");
    }
}

classMyThreadDemo
{
    public static void main(String args[])
    {
        MyThread mt = new  MyThread();
        mt.start();
    }
}
```

Extend?



Hierarchy: Animals

- Animal
  - Mammal
    - Canine
      - Dog
      - Wolf
    - Feline
      - Cat
  - Fish
    - Tuna
    - Shark
  - Reptile
    - Crocodile
    - Iguana

Object - Bank Account

- Accounts have certain data and operations
  - Regardless of whether checking, savings, etc.
- Data
  - account nu
  - balance
  - owner
- Operations
  - open
  - close
  - get balanc
  - deposit
  - withdraw

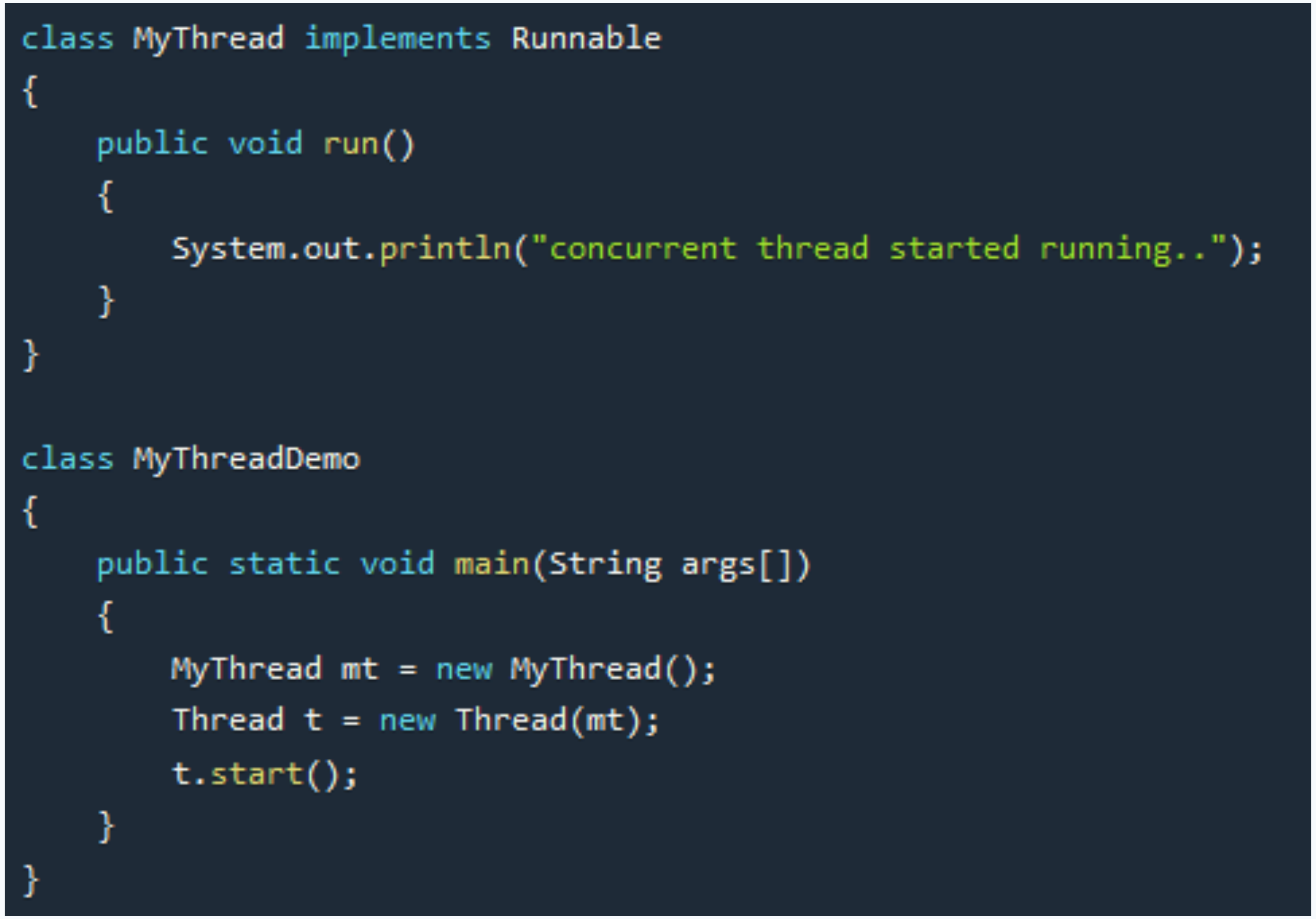
Kinds of Bank Accounts

- Account
  - Checking
    - Monthly fees
    - Minimum balance.
  - Savings
    - Interest rate
- Each type shares some data and operations of "account", and has some data and operations of its own.

Advanced C++ Programming 15

Implement Runnable

- Java does not support multiple inheritance
- If you need your class to inherit



```
class MyThread implements Runnable
{
    public void run()
    {
        System.out.println("concurrent thread started running..");
    }
}

class MyThreadDemo
{
    public static void main(String args[])
    {
        MyThread mt = new MyThread();
        Thread t = new Thread(mt);
        t.start();
    }
}
```

Java threads

Two ways to build multi-threaded programs in Java:

- inherit from class `Thread`, override method `run`
- implement interface `Runnable`, implement method `run`

```
public class Ccounter
   extends Counter
   implements Runnable
{
    // thread's computation:
    public void run() {
      int cnt = counter;
      counter = cnt + 1;
    }
}
```

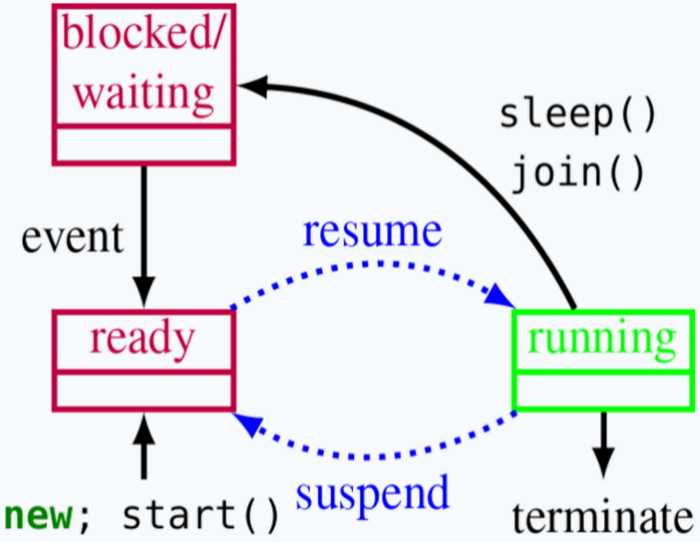
```
CCounter c = new CCounter();

Thread t = new Thread(c);
Thread u = new Thread(c);

t.start();
u.start();
```

Cannot use `Thread` class!

It inherits from Counter

So,
can only use
second method

States of a Java thread

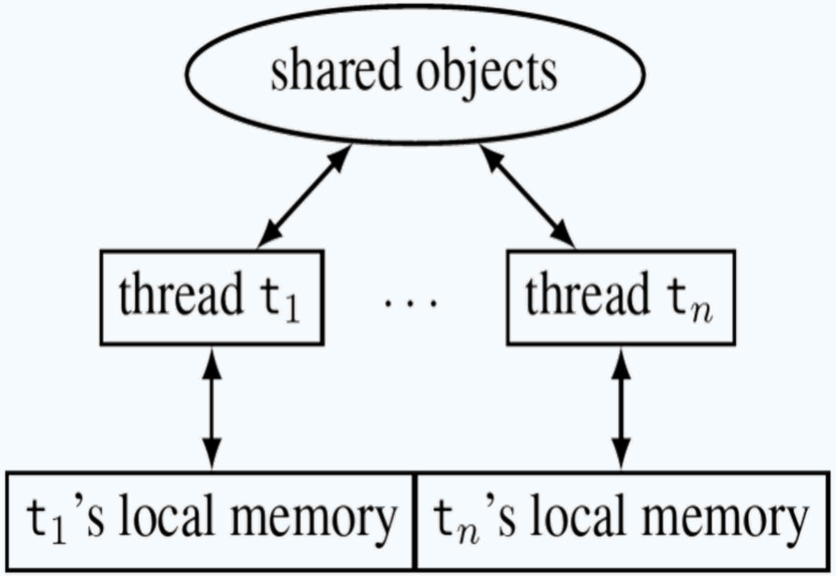


For a `Thread` object `t`:

- `t.start()`: mark the thread `t` ready for execution
- `Thread.sleep(n)`: block the current thread for `n` milliseconds (correct timing depends on JVM implementation)
- `t.join()`: block the current thread until `t` terminates

Resuming and suspending is done by the JVM scheduler, outside the program's control

Thread execution model



Shared vs. thread-local memory:

- Shared objects: the objects on which the thread operates, and all reachable objects
- Local memory: local variables, and special *thread-local* attributes

Threads proceed asynchronously, so they have to coordinate with other threads accessing the same shared objects

One possible execution of the concurrent counter

```
1: public class CCounter implements Runnable {
2:     int counter = 0;        // shared object state
3:
4:     // thread's computation:
5:     public void run() {
6:       int cnt = counter; ● ●
7:       counter = cnt + 1; ● ●
8: } }                      ● ●
```

#	t's LOCAL	u's LOCAL	SHARED
1	$\mathtt{pc}_t : 6\ \mathtt{cnt}_t : \perp$	$\mathtt{pc}_u : 6\ \mathtt{cnt}_u : \perp$	counter: 0
2	$\mathtt{pc}_t : 7\ \mathtt{cnt}_t : 0$	$\mathtt{pc}_u : 6\ \mathtt{cnt}_u : \perp$	counter: 0
3	$\mathtt{pc}_t : 8\ \mathtt{cnt}_t : 0$	$\mathtt{pc}_u : 6\ \mathtt{cnt}_u : \perp$	counter: 1
4	done	$\mathtt{pc}_u : 6\ \mathtt{cnt}_u : \perp$	counter: 1
5	done	$\mathtt{pc}_u : 7\ \mathtt{cnt}_u : 1$	counter: 1
6	done	$\mathtt{pc}_u : 8\ \mathtt{cnt}_u : 1$	counter: 2
7	done	done	counter: **2**

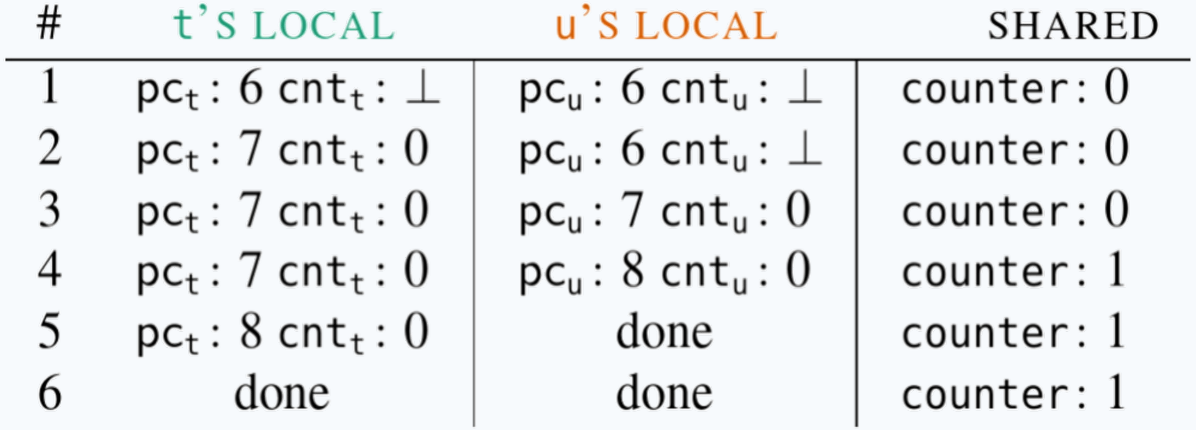
One alternative execution of the concurrent counter

```
1: public class CCounter implements Runnable {
2:     int counter = 0;          // shared object state
3:
4:     // thread's computation:
5:     public void run() {
6:        int cnt = counter; ● ●
7:        counter = cnt + 1; ● ●
8:  } }                      ● ●
```

#	t's LOCAL	u's LOCAL	SHARED
1	$pc_t : 6$ $cnt_t : \bot$	$pc_u : 6$ $cnt_u : \bot$	counter: 0
2	$pc_t : 7$ $cnt_t : 0$	$pc_u : 6$ $cnt_u : \bot$	counter: 0
3	$pc_t : 7$ $cnt_t : 0$	$pc_u : 7$ $cnt_u : 0$	counter: 0
4	$pc_t : 7$ $cnt_t : 0$	$pc_u : 8$ $cnt_u : 0$	counter: 1
5	$pc_t : 8$ $cnt_t : 0$	done	counter: 1
6	done	done	counter: **1**

Traces

Traces



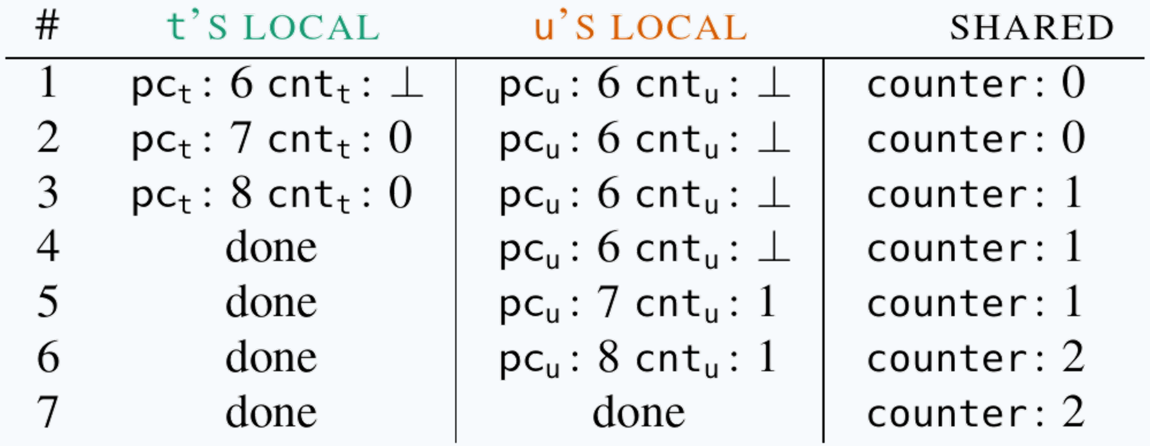
#	T'S LOCAL	U'S LOCAL	SHARED
1	$pc_t : 6$ $cnt_t : \bot$	$pc_u : 6$ $cnt_u : \bot$	$counter : 0$
2	$pc_t : 7$ $cnt_t : 0$	$pc_u : 6$ $cnt_u : \bot$	$counter : 0$
3	$pc_t : 7$ $cnt_t : 0$	$pc_u : 7$ $cnt_u : 0$	$counter : 0$
4	$pc_t : 7$ $cnt_t : 0$	$pc_u : 8$ $cnt_u : 0$	$counter : 1$
5	$pc_t : 8$ $cnt_t : 0$	done	$counter : 1$
6	done	done	$counter : 1$

A trace is an abstraction of concrete executions:

- atomic/linearized
- complete
- interleaved

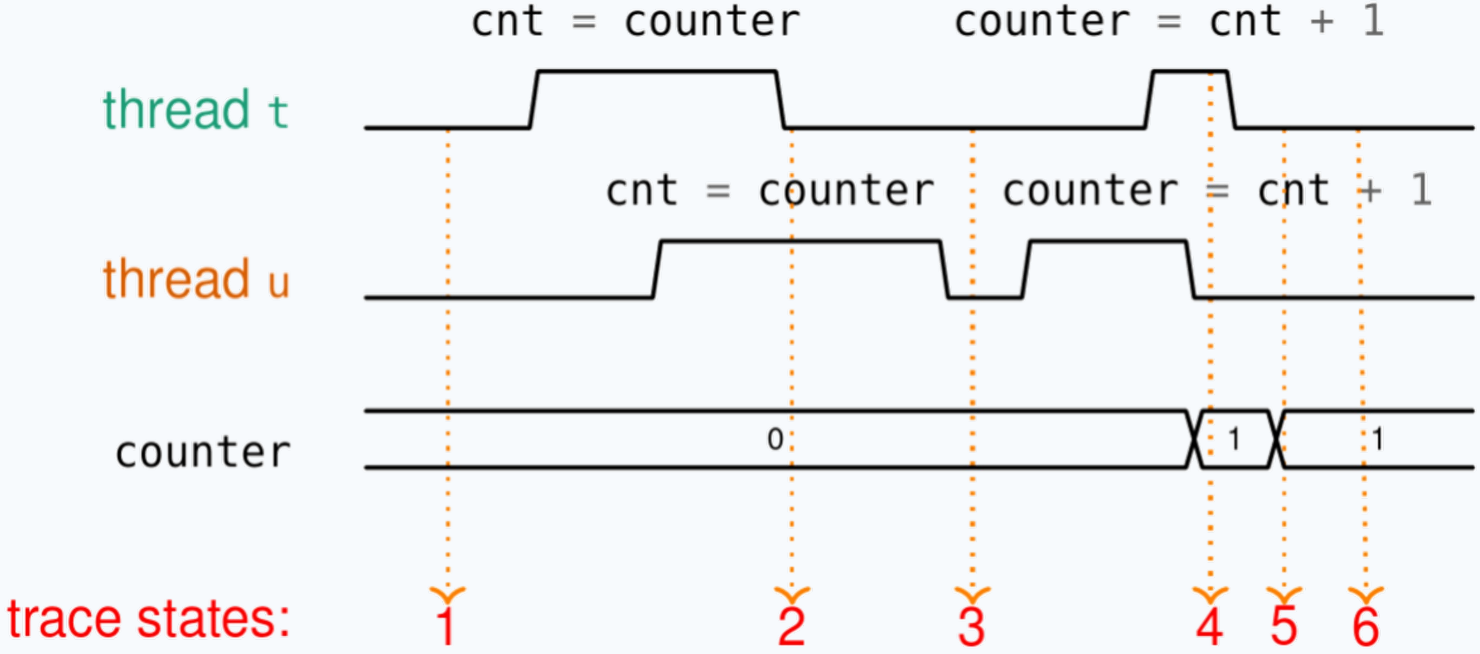
The sequence of states gives an execution trace of the concurrent program

Another **trace**
A different
interleaving



#	T'S LOCAL	U'S LOCAL	SHARED
1	$pc_t : 6$ $cnt_t : \bot$	$pc_u : 6$ $cnt_u : \bot$	$counter : 0$
2	$pc_t : 7$ $cnt_t : 0$	$pc_u : 6$ $cnt_u : \bot$	$counter : 0$
3	$pc_t : 8$ $cnt_t : 0$	$pc_u : 6$ $cnt_u : \bot$	$counter : 1$
4	done	$pc_u : 6$ $cnt_u : \bot$	$counter : 1$
5	done	$pc_u : 7$ $cnt_u : 1$	$counter : 1$
6	done	$pc_u : 8$ $cnt_u : 1$	$counter : 2$
7	done	done	$counter : 2$

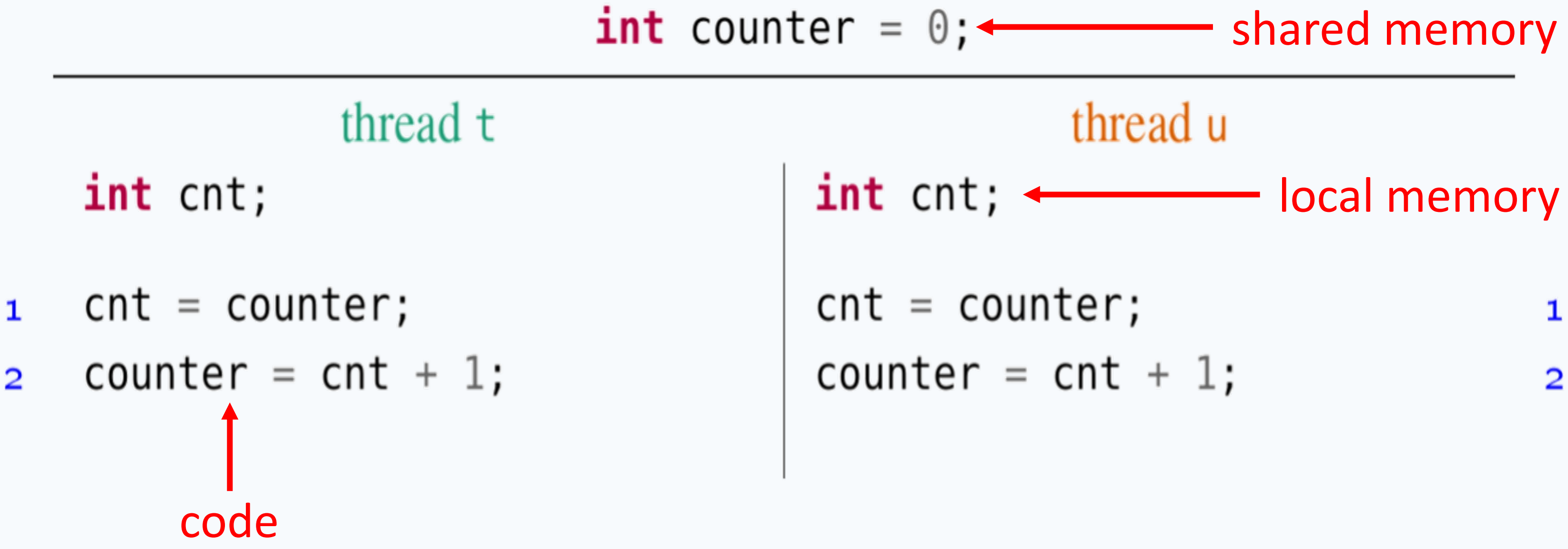
Trace abstractions



Atomic/linearized:	The effects of each thread appear as if they happened instantaneously, when the trace snapshot is taken, in the thread’s sequential order
Complete:	The trace includes all intermediate atomic states
Interleaved:	The trace is an interleaving of each thread’s linear trace (in particular, no simultaneity)

Abstraction of concurrent programs

When convenient, we will use an abstract notation for multi-threaded applications, which is similar to the pseudo-code used in Ben-Ari's book but uses Java syntax



```
                    int counter = 0;
-----------------------------------------------------------
         thread t               |          thread u
  int cnt;                      |  int cnt;
                                |
  cnt = counter;                |  cnt = counter;
  counter = cnt + 1;            |  counter = cnt + 1;
```

shared memory

local memory

code

Each line of code includes exactly one instruction that can be executed atomically:

- atomic statement ≅ single read or write to global variable
- precise definition is tricky in Java, but we will learn to avoid pitfalls