Concepts of Concurrent Computation

Spring 2015

Lecture 1: Overview

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Practical details

- Schedule

Tuesday	10-12	RZ F 21	lecture
Wednesday	14-15	RZ F 21	exercise class
Wednesday	15-17	RZ F 21	seminar

- Course page

  http://se.inf.ethz.ch/courses/2015a_spring/ccc/

- Lecturers
  - Dr. Sebastian Nanz
  - Dr. Chris Poskitt
- Assistants
  - Chandrakana Nandi (exercise class)
  - Mischael Schill (project)

Grading

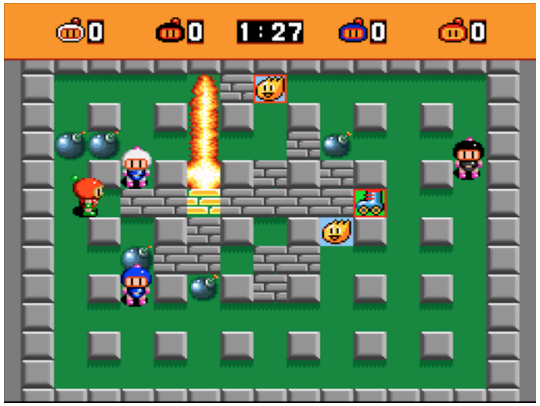
- **Exam: 50%**
  - End-of-semester exam
  - Date: **26 May 2015** (at the usual lecture time)

- **Project: 35%**
  - Build a small concurrent system

- **Seminar talk: 15%**
  - Present a recent research paper

Project

- Organization
  - Teams of 1-3 students
  - Multiple deadlines/milestones
  - Support: Mischael Schill + mailing list
- Project overview
  - “Bomberman” game
  - Less concurrency-relevant code given
  - Implemented using SCOOP



- What is SCOOP?
  - A high-level programming model for concurrency
  - Covered in a future lecture
  - For ease of installation, programming framework and project files provided as virtual machine

Seminar: Overview

- The seminar connects the course topics to recent research results
    - Research papers from 2011-2014
- The seminar consists of student presentations
    - 15 min paper presentation (with slides) + questions
- The seminar lives from discussions about the papers
    - Read papers and prepare questions in advance

Seminar: Grading

- **Content**
  - Technical correctness
  - Coherent development of concepts
  - Selection of content
  - Visualization of content
  - **Own contributions: own examples, own evaluation, tracing of the paper's impact**
- **Presentation**
  - Slides (style, grammar, spelling)
  - Use of other aids
  - Voice & speech
  - Audience engagement/stage presence
  - Timing/pace

Seminar: Paper selection

- You will get an email today, with a list of papers and instructions for telling us your choice (doodle)
- Respond no later than **this Friday, 20 February, 12:00**
- If you don’t get the email today or miss the deadline, please email the assistants

- **Tomorrow, 18 February:**
  - **14:15 First exercise class**
  - **Hand-out of the project description**
  - No seminar: use the time for paper selection

Purpose of the course

- To introduce you to the main concurrency approaches and give you an idea of their strength and weaknesses
  - Practical approaches to concurrent programming
  - Modelling and reasoning about concurrency
- To enable you to get a concrete grasp of the issues and solutions through a course project
- To connect to recent research through a seminar

Course overview

- Practical approaches to concurrent programming
  - Issues: data races, deadlock, starvation
  - Synchronization algorithms
  - Semaphores
  - Monitors
  - Language examples: SCOOP and others
  - Lock-free programming and Software Transactional Memory
- Modelling and reasoning about concurrency
  - Proofs of concurrent programs
  - Temporal logic
  - Petri nets
  - Process calculi: CCS

Crossing the chasm

- Formal models provide an elegant theoretical basis, but
    - Have little connection with practice
    - Handle concurrency aspects only
- Practice of concurrent programming
    - Little influenced by above
    - Low-level mechanisms still predominant
- In the course, we look at both theoretical and practical approaches to concurrency

Recommended textbooks

- Mordechai Ben-Ari. Principles of Concurrent and Distributed Programming. Prentice Hall, 2006
- Maurice Herlihy and Nir Shavit. The Art of Multiprocessor Programming. Morgan Kaufmann, 2008
- Gregory R. Andrews. Foundations of Multithreaded, Parallel, and Distributed Programming. Addison Wesley, 1999
- Draft of a textbook for this course

- More literature recommendations: see individual lectures

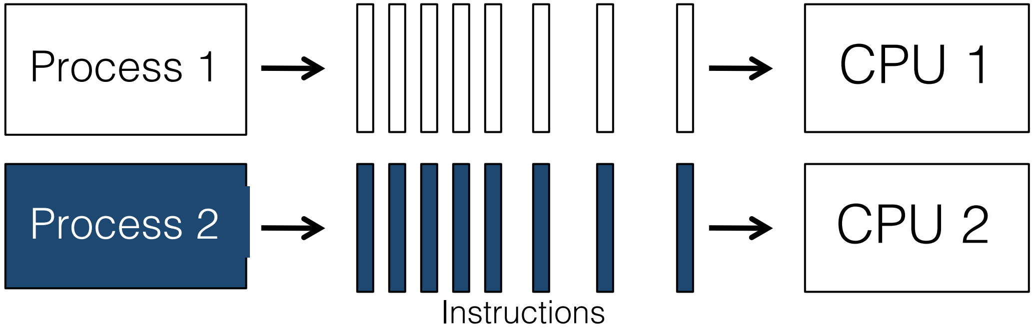
What is concurrency?

Origins of concurrency in computing

- Concurrency is not a new topic but one most programmers have been able to avoid
- Previously perceived as a very specialized topic
    - **Systems programming**
    - Databases
    - High-performance computing

Multiprocessing

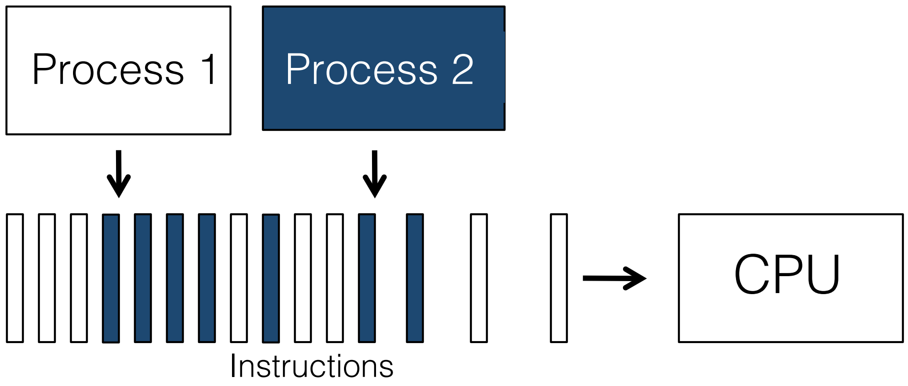
- Many of today's computations can take advantage of multiple processing units (multi-core processors)



- Multiprocessing: the use of more than one processing unit in a system
- Execution of processes is said to be parallel, as they are running at the same time

Multitasking/multithreading

- Even on systems with a single processing unit we may give the illusion of that several programs run at once



- Multitasking/multithreading: the operating system switches between the execution of different tasks/threads
- Execution of processes is said to be interleaved, as all are in progress, but only one is running at a time

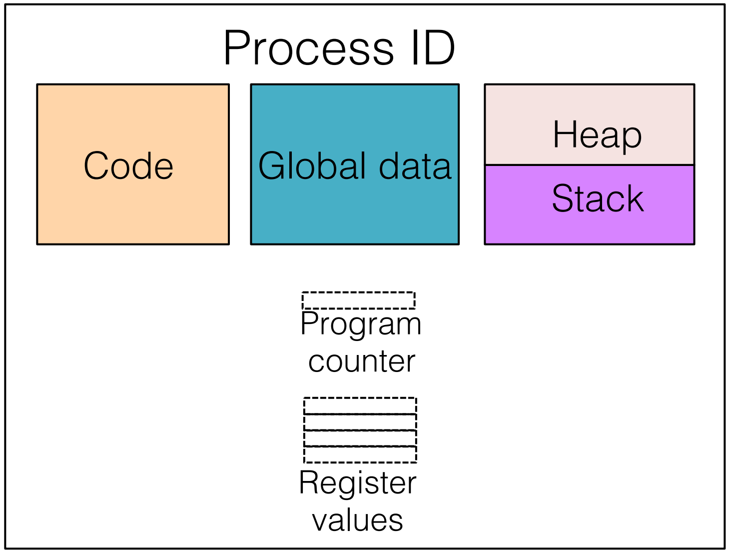
Concurrency ≠ Parallelism

- Both multiprocessing and multitasking are examples of concurrent computation
- The execution of processes is said to be concurrent if it is either parallel or interleaved
- In this terminology, parallelism is a form of concurrency

- In programming, the terms are often used to emphasize the type of problem they solve
  - Concurrent programming: nondeterministic composition of independently executing processes
  - Parallel programming: efficient execution of a deterministic computation on multiple processing units

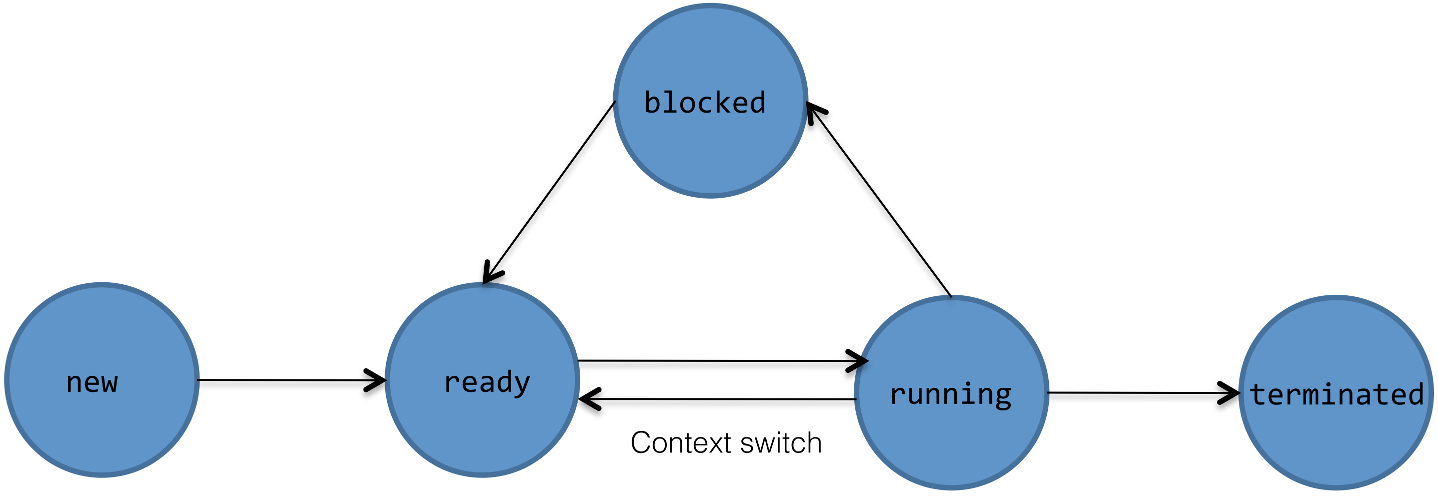
Operating system processes

- How are processes implemented in an operating system?
- Structure of a typical process:
    - Process identifier: unique ID of a process.
    - Process state: current activity of a process.
    - Process context: program counter, register values.
    - Memory: program text, global data, stack, and heap.



The scheduler

- A system program called the scheduler controls which processes are running
- The scheduler sets the process states:
  - `new`: being created
  - `running`: instructions are being executed
  - `blocked`: currently waiting for an event
  - `ready`: ready to be executed, but not assigned to a processor
  - `terminated`: finished executing

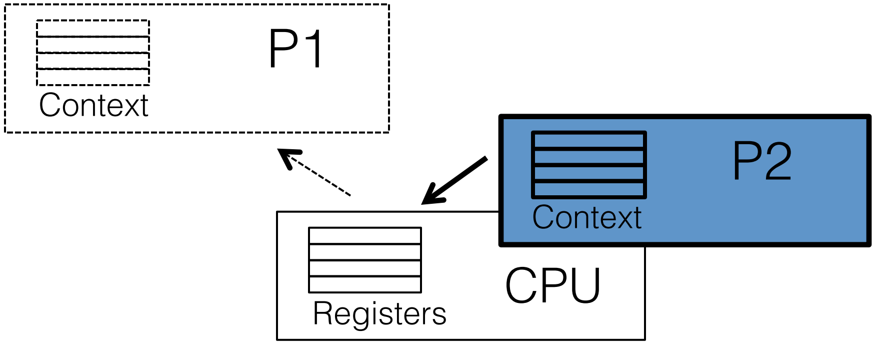


Blocked processes

- A process can get into state `blocked` by executing special program instructions (synchronization primitives)
- When blocked, a process cannot be selected for execution
- A process gets unblocked by external events which set its state to `ready` again

The context switch

- The swapping of processes on a processing unit by the scheduler is called the context switch

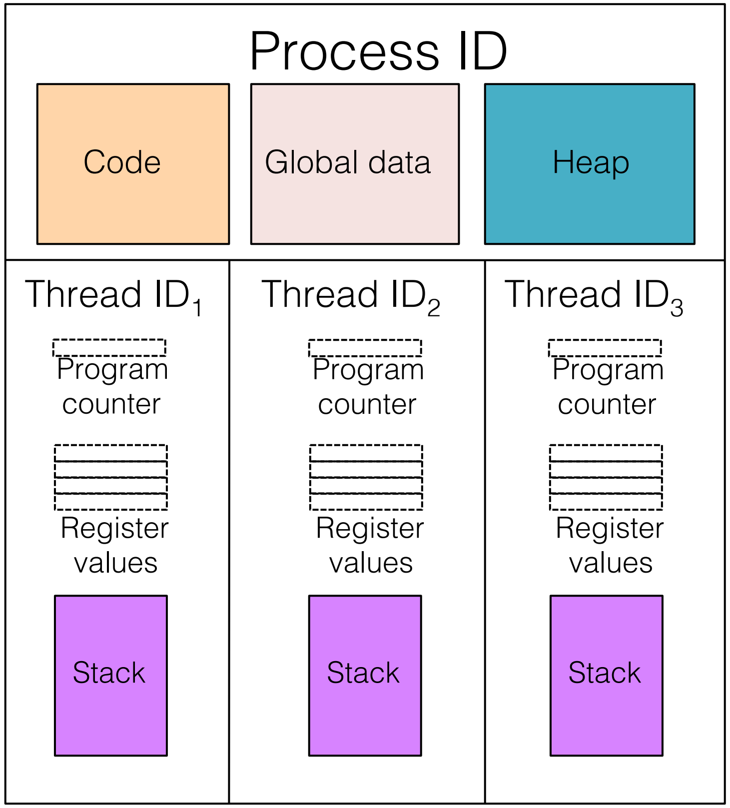


- Scheduler actions when switching processes P1 and P2:

```
P1.state := ready
// Save register values as P1's context in memory
// Use context of P2 to set register values
P2.state := running
```

Threads

- Make programs concurrent by associating them with threads
- A thread is a part of an operating system process
- Private components
  - Thread identifier
  - Thread state
  - Thread context
  - Memory: only stack
- Shared components
  - Program text
  - Global data
  - Heap



Expressing concurrency

Example: Java Threads

- How to associate computations with threads in Java?
  - Inherit from **`Thread`**, or
  - Implement the **`Runnable`** interface

```java
class Worker implements Runnable {
  private int input;
  private int result;

  public Worker(int i) {
    input = i;
  }
  public void run() {
    // computation
  }
  public int getResult() {
    return result;
  }
}
```

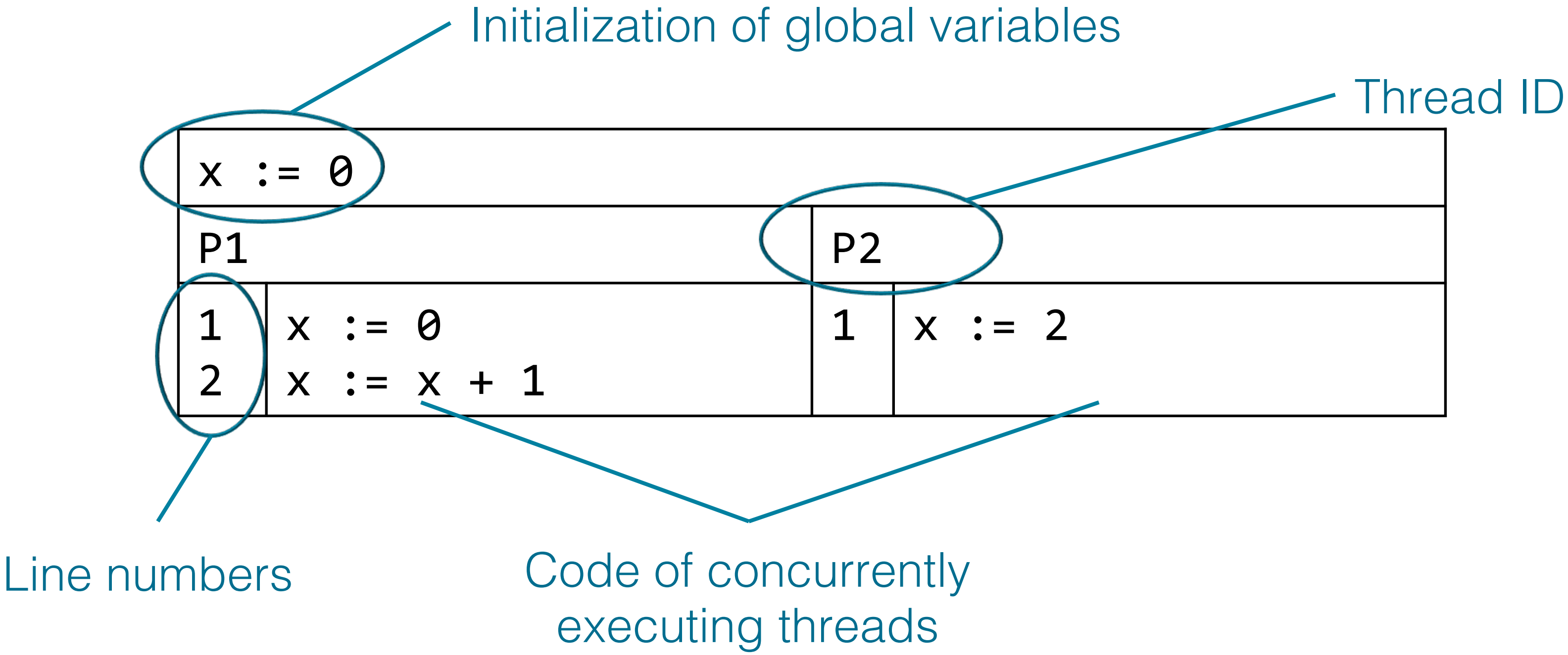
```java
void compute() {
  Worker w1 = new Worker(23);
  Worker w2 = new Worker(42);

  Thread t1 = new Thread(w1);
  Thread t2 = new Thread(w2);

  t1.start();
  t2.start();
}
```

Abstract notation

- A program which at runtime gives rise to a process containing multiple threads is called a concurrent program
- How to specify threads? Every programming language provides a different syntax
- We use an abstract notation for concurrent programs



Initialization of global variables

Thread ID

x := 0			
P1		P2	
1 2	x := 0 x := x + 1	1	x := 2

Line numbers

Code of concurrently executing threads

Execution sequences

<table>
<tr><td colspan="4"><code>x := 0</code></td></tr>
<tr><td colspan="2"><code>P1</code></td><td colspan="2"><code>P2</code></td></tr>
<tr><td><code>1</code>
<code>2</code></td><td><code>x := 0</code>
<code>x := x + 1</code></td><td><code>1</code></td><td><code>x := 2</code></td></tr>
</table>

- Execution can give rise to this execution sequence

Instruction executed
with Thread ID and
line number

Variable values after
execution of the code
on the line

`P1`	`1`	`x := 0`	`x = 0`
`P2`	`1`	`x := 2`	`x = 2`
`P1`	`2`	`x := x + 1`	`x = 3`

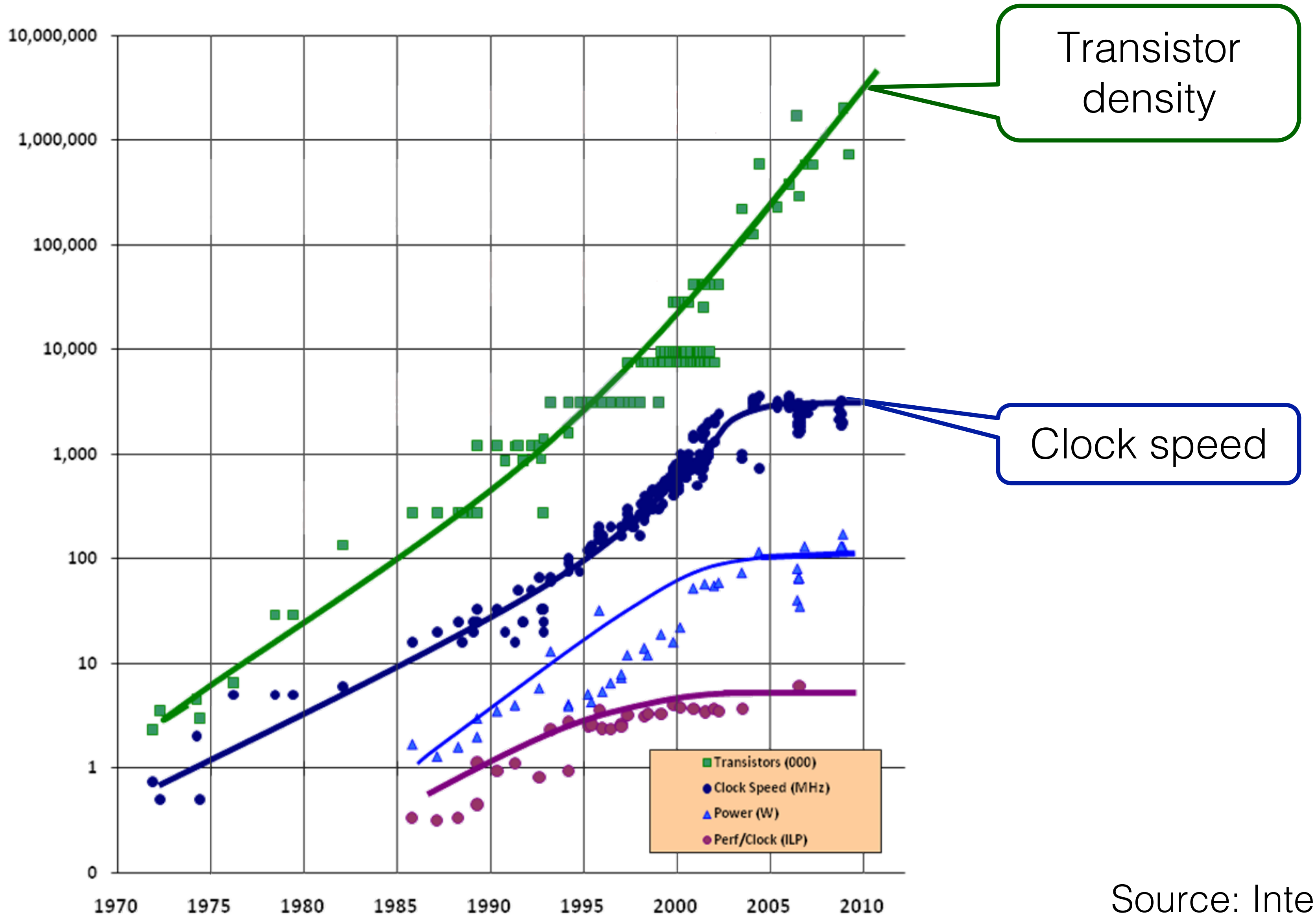
- Is this the only possible execution sequence?

Benefits and challenges of concurrency

Why concurrency?

- Responsiveness
  - GUI programming
  - Network programming
  - Communicating with multiple hardware devices
- Program structuring
  - Handle nondeterministic events in a modular way
  - Model concurrency in the real world
- Performance
  - Speeding up computations

The end of Moore‘s Law as we knew it



Transistor density

Clock speed

Source: Intel

Why do we care?

- The “end of Moore’s law as we knew it” has important implications on the software construction process
- Computing is taking an irreversible step toward parallel architectures
  - Hardware construction of ever faster sequential CPUs has hit physical limits
  - Clock speed no longer increases for every new processor generation
  - Moore’s Law expresses itself as exponentially increasing number of processing cores per chip
- If we want programs to run faster on the next processor generation, the software must exploit more concurrency

Amdahl’s Law

- We go from 1 processor to n processors. What gain may we expect?
- Amdahl’s law severely limits our hopes!
- Define gain as:

$$\text{speedup} = \frac{\text{old\_execution\_time}}{\text{new\_execution\_time}}$$

- Not everything can be parallelized!

$$\text{speedup} = \frac{1}{\underbrace{\boxed{1 - p}}_{\text{Sequential part}} + \underbrace{\boxed{(\underbrace{\boxed{p}}_{\text{\% parallelizable}} / \underbrace{\boxed{n}}_{\text{Number of processors}})}}_{\text{Parallel part}}}$$

Amdahl’s law: Example (1)

- Assume 10 processing units. How close are we to a 10-fold speedup?
  - 60% concurrent, 40% sequential:

$$\text{speedup} = \frac{1}{1 - 0.6 \quad + \quad (0.6 / 10)} = 2.17$$

  - 80% concurrent, 20% sequential:

$$\text{speedup} = \frac{1}{1 - 0.8 \quad + \quad (0.8 / 10)} = 3.57$$

Amdahl’s law: Example (2)

- 90% concurrent, 10% sequential:

$$\text{speedup} = \frac{1}{1 - 0.9 \quad + \quad (\,0.9 \,/\, 10\,)} = 5.26$$

- 99% concurrent, 1% sequential:

$$\text{speedup} = \frac{1}{1 - 0.99 \quad + \quad (\,0.99 \,/\, 10\,)} = 9.17$$

Types of concurrent computation

Types of parallel computation

- Flynn's taxonomy: classification of computer architectures
- Considers relationships of instruction streams to data streams

	Single Instruction	**Multiple Instruction**
Single Data	SISD	
Multiple Data	SIMD	MIMD

SISD
No parallelism
(uniprocessor)

SIMD
Vector processor
GPU

MIMD
Multiprocessing
(predominant today)

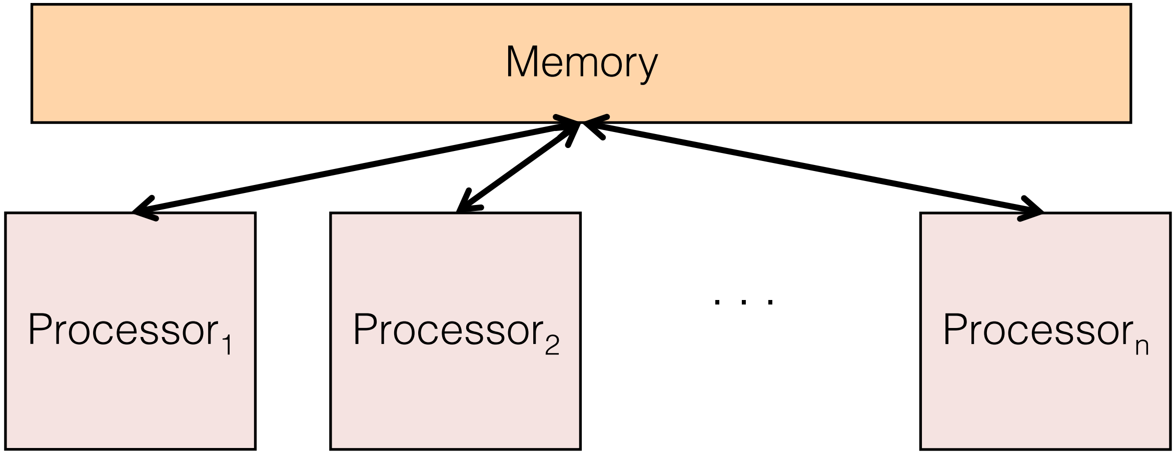
MIMD variants

- SPMD (Single Program Multiple Data)
  - All processors run the same program, but at independent speeds
  - No lockstep as in SIMD

- MPMD (Multiple Program Multiple Data)
  - Often manager/worker strategy: manager distributes tasks, workers return result to manager

Shared memory model

- All processors share a common memory
- Shared-memory communication



Memory

Processor$_1$

Processor$_2$

. . .

Processor$_n$

Distributed memory model

- Each processor has own local memory, inaccessible to others
- Message-passing communication
- Common for SPMD architecture