



# Concepts of Concurrent Computation

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## Lecture 2: Challenges of Concurrency

# Today's lecture

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In this lecture you will learn about:

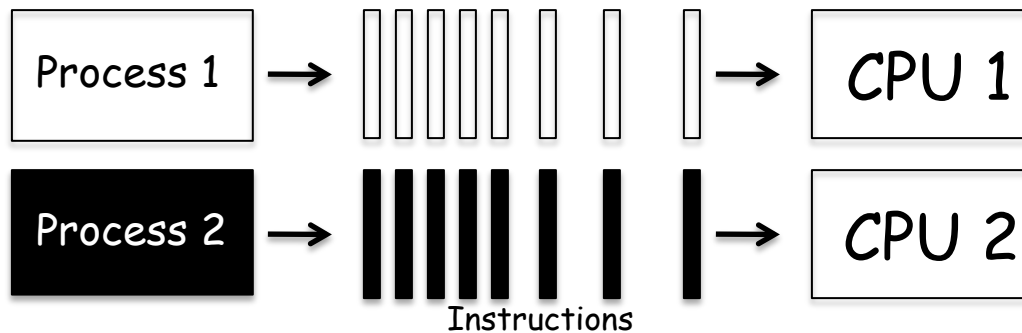
- the basics of **concurrent execution of processes** in operating systems (multiprocessing, multitasking)
- the **interleaving semantics** of concurrent computation, and a formalization (transition systems, **temporal logic**)
- the most important problems related to concurrent programming (**race conditions, deadlock, starvation**)



# Concurrent Processes

# Multiprocessing, parallelism (Recap)

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



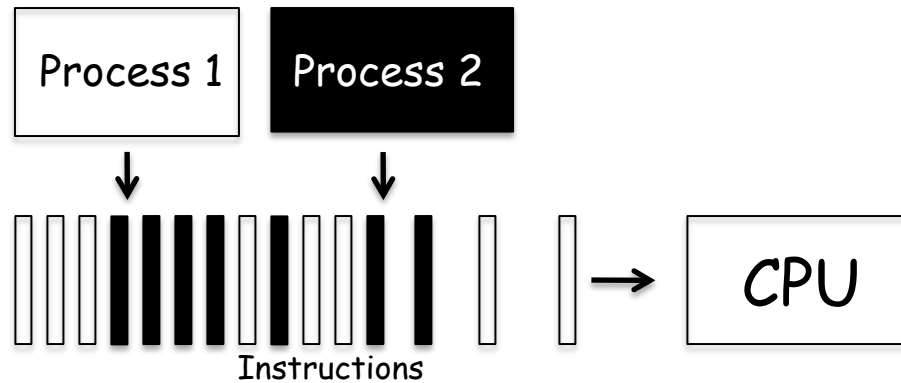
Terminology:

- **Multiprocessing**: the use of more than one processing unit in a system
- **Parallel execution**: processes running at the same time

# Multitasking, concurrency (Recap)

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

The OS switches between executing different tasks



Terminology:

- **Interleaving:** several tasks active, only one running at a time
- **Multitasking:** the OS runs interleaved executions
- **Concurrency:** multiprocessing, multitasking, or any combination

# Processes

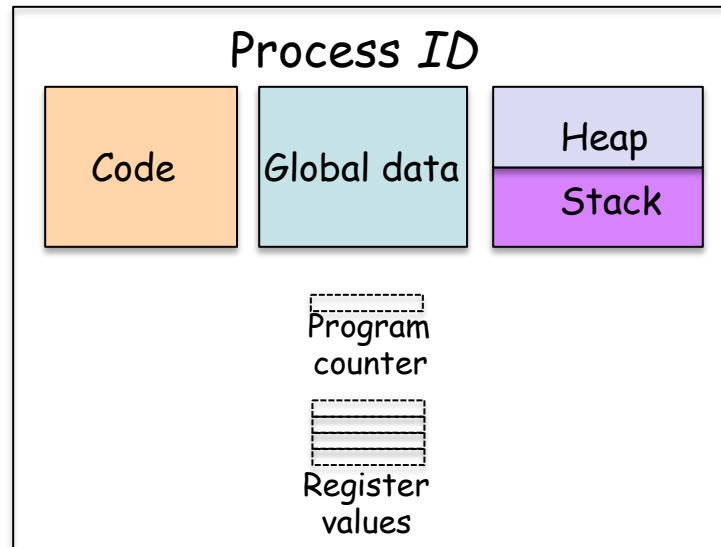
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- A (sequential) *program* is a set of instructions
- A *process* is an instance of a program that is being executed

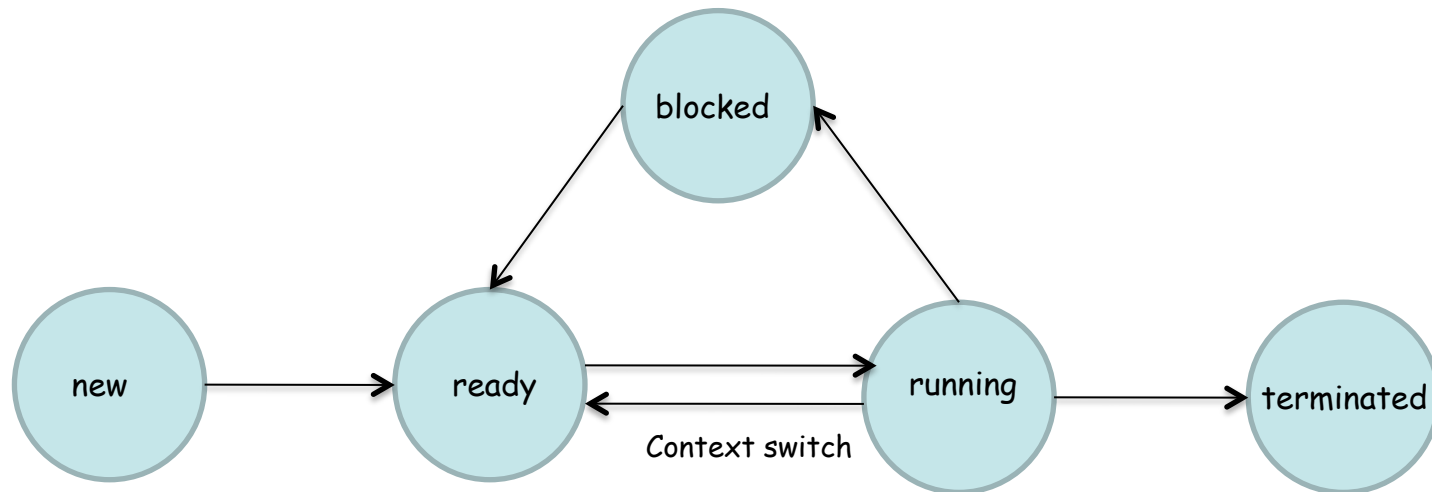
# Operating system processes

- 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; it 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 been assigned a processor yet.
  - *terminated*: finished executing.



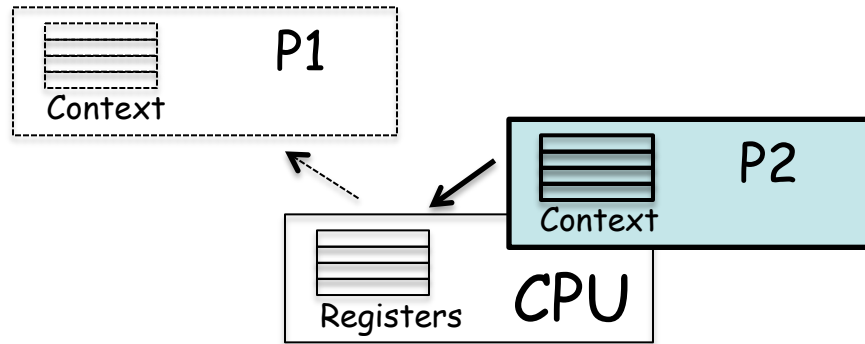




- A process can get into state *blocked* by executing special program instructions (synchronization primitives, see following lectures)
- When blocked, a process cannot be selected for execution
- A process gets unblocked by external events which set its state to *ready* again

# The context switch

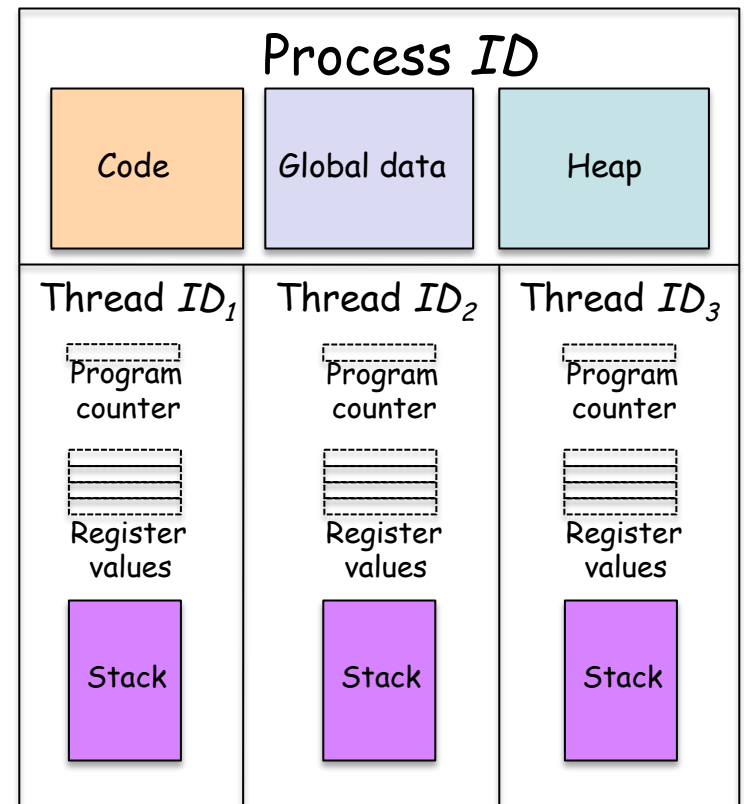
- The swapping of processes on a processing unit by the scheduler is called the *context switch*



- 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
  - $P2.state := running$

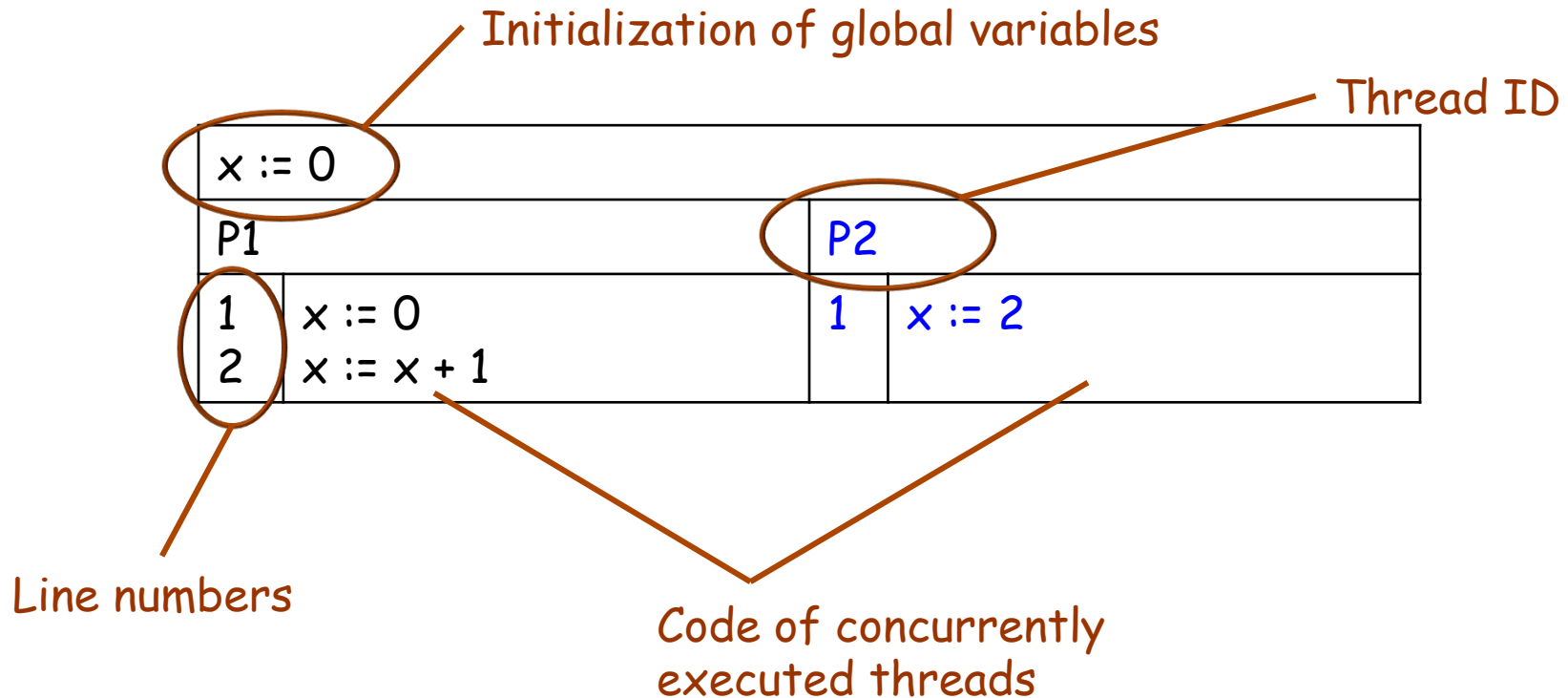
# Threads

- Make programs concurrent by associating them with threads
- A *thread* is a part of an operating system process
- Components private to each thread
  - Thread identifier
  - Thread state
  - Thread context
  - Memory: only stack
- Components shared with other threads:
  - Program text
  - Global data
  - Heap



# Concurrent programs

- 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 different syntax.
- Abstract notation for a concurrent program:



# Execution sequences

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

- Execution can give rise to this *execution sequence*:

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

Instruction executed with Thread ID and line number

Variable values after execution of the code on the line

# Execution sequences



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

- Considering all interleavings, execution can give rise to the following execution sequences:

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

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

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

# Race conditions

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- If processes/threads are completely independent, concurrency is easy
- Much more often threads *interfere* with each other, for example by accessing and modifying the same variables or objects
- The situation that the result of a concurrent execution is dependent on the nondeterministic interleaving is called a *race condition* or *data race*
- Such errors can stay hidden for a long time and are difficult to find by testing

# Atomic instructions

- An instruction is *atomic* if its execution cannot be interleaved with other instructions before its completion
- We can choose different levels of atomicity

The choice is important: for example, the instruction

`x := x + 1`

is on many systems executed as:

`temp := x`

-- LOAD R0, x

`temp := temp + 1`

-- ADD R0, #1

`x := temp`

-- STORE R0, x

- Convention: in our notation for concurrent programs, every numbered line can be executed atomically



# Choice of atomicity level

- To reflect the different assumption on atomicity, the concurrent program is restated:

x := 0			
P1		P2	
1	x := 0	1	x := 2
2	temp := x		
3	temp := temp + 1		
4	x := temp		

- One of the possible execution sequences:

P1	1	x := 0	x = 0
P1	2	temp := x	x = 0, temp = 0
P2	1	x := 2	x = 2, temp = 0
P1	3	temp := temp + 1	x = 2, temp = 1
P1	4	x := temp	x = 1, temp = 1

# Java Threads: defining threads

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

```
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;
    }
}
```

```
void compute() {
    Worker worker1 = new Worker(23);
    Worker worker2 = new Worker(42);

    Thread t1 = new Thread(worker1);
    Thread t2 = new Thread(worker2);

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

# Java Threads: Joining threads

- Often the final results of thread executions need be combined

```
return worker1.getResult() + worker2.getResult();
```

- We have to wait for both threads to be finished: we have to *join* the threads

```
t1.start();  
t2.start();  
t1.join();  
t2.join();  
return worker1.getResult() + worker2.getResult();
```

- The *join()* method, when invoked on a thread *t* causes the caller to wait until *t* is finished



# The interleaving semantics

# True-concurrency vs. interleaving semantics

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- To describe concurrent behavior, we need a *model*
- *True-concurrency semantics*: assumption that true parallel behaviors exist
- *Interleaving semantics*: assumption that all parallel behavior can be represented by the set of all non-deterministic interleavings of *atomic instructions*



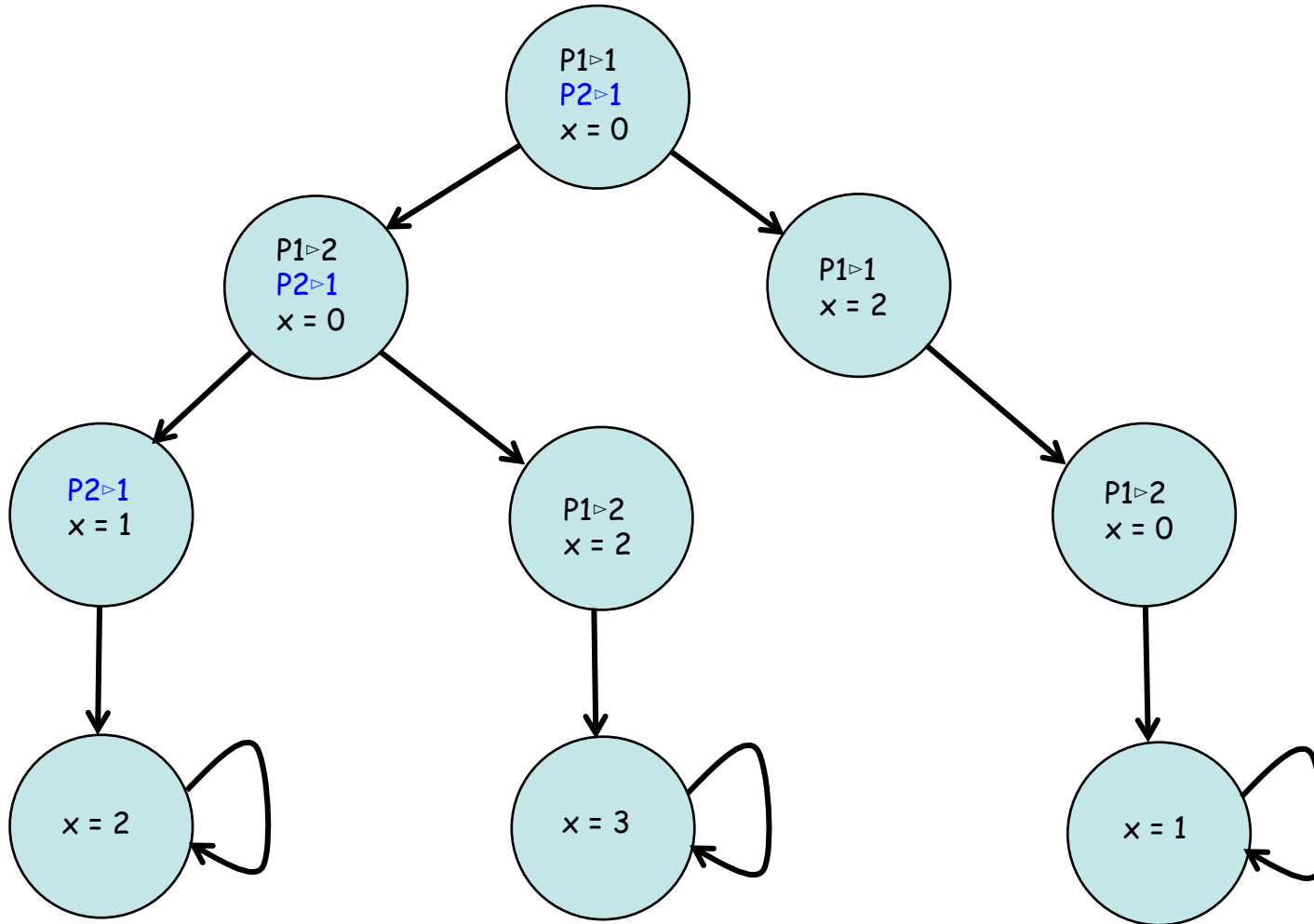
- The interleaving semantics provides a good model for concurrent programs, in particular it can describe:
  - Multitasking: The interleaving is performed by the scheduler
  - Multiprocessing: The interleaving is performed by the hardware
- By considering all possible interleavings, we can ensure that a program runs correctly in all possible scenarios
- Downside: The number of possible interleavings grows exponentially in the number of concurrent processes (*state space explosion* problem)

# Transition systems

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- A formal model that allows us to express concurrent computation are *transition systems*
- They consist of states and transitions between them
- A state is labeled with *atomic propositions*, which express concepts such as:
  - $P2 \triangleright 2$  (the program pointer of P2 points to 2)
  - $x = 6$  (the value of variable x is 6)
- There is a transition between two states if one state can be reached from the other by executing an atomic instruction

# Example: transition system



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



# Transition systems, formally

- Let  $A$  be a set of atomic propositions
- A *transition system*  $T$  is a triple  $(S, \rightarrow, L)$  where
  - $S$  is the *set of states*
  - $\rightarrow \subseteq S \times S$  is the *transition relation*
  - $L : S \rightarrow 2^A$  is the *labeling function*
- The transition relation has the additional property that for every  $s \in S$  there is an  $s' \in S$  such that  $s \rightarrow s'$
- A path is an infinite sequence of states

$$\pi = s_1, s_2, s_3, \dots$$

such that for every  $i \geq 1$  we have  $s_i \rightarrow s_{i+1}$

- We write  $\pi[i]$  for the subsequence  $s_i, s_{i+1}, s_{i+2}, \dots$

- For any concurrent program, its transition system represents all of its behavior
- We are typically interested in specific aspects of this behavior, e.g.
  - "the value of variable  $x$  will never be negative"
  - "the program pointer of P2 will eventually point to 9"
- Temporal logics allow us to express such properties formally
- We will study *linear-time temporal logic* (LTL)

# Syntax of LTL

- The **syntax of LTL formulas** is given by the following grammar:

$$\phi ::= \top \mid p \mid \neg\phi \mid \phi \wedge \phi \mid \mathbf{G}\phi \mid \mathbf{F}\phi \mid \phi \mathbf{U}\phi \mid \mathbf{X}\phi$$

- Formulas known from propositional logic:

$$\top \mid p \mid \neg\phi \mid \phi \wedge \phi$$

- Temporal operators:

- $\mathbf{G}\phi$ : *Globally* (in all future states)  $\phi$  holds
  - $\mathbf{F}\phi$ : in some *Future* state  $\phi$  holds
  - $\phi_1 \mathbf{U}\phi_2$ : in some future state  $\phi_2$  holds, and at least *Until* then,  $\phi_1$  holds
  - $\mathbf{X}\phi$ : in the *Next* state,  $\phi$  holds
- Sometimes we write  $\square$  instead of  $\mathbf{G}$ , and  $\diamond$  instead of  $\mathbf{F}$

- The meaning of formulas is defined by the satisfaction relation  $\models$  for a path  $\pi = s_1, s_2, s_3, \dots$

$$\pi \models \top$$

$$\pi \models p \quad \text{iff } p \in L(s_1)$$

$$\pi \models \neg\phi \quad \text{iff } \pi \models \phi \text{ does not hold}$$

$$\pi \models \phi_1 \wedge \phi_2 \quad \text{iff } \pi \models \phi_1 \text{ and } \pi \models \phi_2$$

$$\pi \models \mathbf{G} \phi \quad \text{iff for all } i \geq 1, \pi[i] \models \phi$$

$$\pi \models \mathbf{F} \phi \quad \text{iff exists } i \geq 1, \text{ such that } \pi[i] \models \phi$$

$$\pi \models \phi_1 \mathbf{U} \phi_2 \quad \text{iff exists } i \geq 1, \text{ such that } \pi[i] \models \phi_2 \text{ and} \\ \text{for all } 1 \leq j < i, \pi[j] \models \phi_1$$

$$\pi \models \mathbf{X} \phi \quad \text{iff } \pi[2] \models \phi$$

- If we write  $s \models \phi$  we mean that for every path  $\pi$  starting in  $s$  we have  $\pi \models \phi$

# Example: LTL formulas

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- "the value of variable x will never be negative"

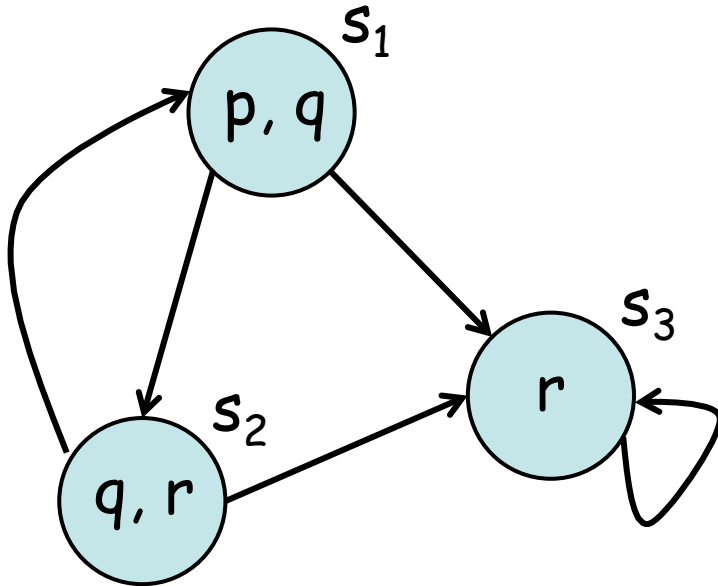
$G \neg(x < 0)$

- "whenever the program pointer of P2 points to 3, it will eventually point to 9"

$G (P2 \triangleright 3 \rightarrow F P2 \triangleright 9)$

# Example: semantics of LTL

- Consider the following transition system:



- Which properties hold?
  - $s_1 \models p \wedge q$
  - $s_1 \models \mathbf{G} \neg(p \wedge r)$
  - $s_1 \models \mathbf{X} q$
  - $s_1 \models \mathbf{F} (\neg q \wedge r) \rightarrow \mathbf{F} \mathbf{G} r$

# Equivalence of formulas



- Two formulas  $\varphi$  and  $\psi$  are *equivalent* if for all transition systems and all paths  $\pi$   
$$\pi \models \varphi \text{ iff } \pi \models \psi$$
- Some equivalent formulas:
  - $\mathbf{F} \varphi \equiv \mathbf{T} \mathbf{U} \varphi$
  - $\mathbf{G} \varphi \equiv \neg \mathbf{F} \neg \varphi$
- Hence both  $\mathbf{F}$  and  $\mathbf{G}$  can be expressed by  $\mathbf{U}$
- $\mathbf{X}$  cannot be expressed in terms of the others
- $\mathbf{X}$  and  $\mathbf{U}$  form an *adequate set* of temporal connectives, i.e. all temporal operators can be defined in terms of these

# Safety and liveness properties

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- There are two types of formal properties in asynchronous computation:
  - *Safety properties*: properties of the form "nothing bad ever happens"
  - *Liveness properties*: properties of the form "something good eventually happens"
- Example (safety): "the value of variable x will never be negative"
- Example (liveness): "whenever the program pointer of P2 points to 3, it will eventually point to 9"
- Safety properties are often expressible with the LTL formula  $\mathbf{G} \neg\phi$ , and liveness properties with  $\mathbf{G} (\phi \rightarrow \mathbf{F} \psi)$



# Synchronization

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- In order to solve the problem of data races, processes have to *synchronize* with each other
- *Synchronization* describes the idea that processes communicate with each other in order to agree on a sequence of actions
- In the above example, it could be agreed that only one process at a time can *hold* the resource (have exclusive use of it); we will see techniques for this in later lectures
- How can processes communicate?

- Two main means of process communication:
  - *Shared memory*: processes communicate by reading and writing to shared sections of memory
  - *Message-passing*: processes communicate by sending messages to each other



# Deadlock and starvation

# The problem of deadlock

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- The ability to hold resources exclusively is central to providing process synchronization for resource access
- Unfortunately, it brings about other problems
- A *deadlock* is the situation where a group of processes blocks forever because each of the processes is waiting for resources which are held by another process in the group
- An illustrative example of deadlock is the *dining philosopher's problem*

# The dining philosophers problem

- $n$  philosophers are seated around a table and in between each pair of philosophers there is a single fork.
- In order to eat, each philosopher needs to pick up both forks which are lying to his sides, and thus philosophers sitting next to each other can never eat at the same time.
- A philosopher only engages in two activities: thinking and eating.
- The problem consist of devising an algorithm such that the following properties are ensured:
  - Each fork is held by one philosopher at a time
  - Philosophers don't deadlock



# Dining philosophers: solution attempt 1

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- Each philosopher first picks up the right fork, then the left fork, and then starts eating; after having eaten, the philosopher puts down the left fork, then the right one
- The philosophers can deadlock

# The Coffman conditions

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- There are a number of necessary conditions for deadlock to occur
  1. *Mutual exclusion*: processes have exclusive control of the resources they require
  2. *Hold and wait*: processes already holding resources may request new resources
  3. *No preemption*: resources cannot be forcibly removed from a process holding it
  4. *Circular wait*: two or more processes form a circular chain where each process waits for a resource that the next process in the chain holds
- Attempts at avoiding deadlocks typically **try to break one of these conditions**

## Dining philosophers: solution attempt 2

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- Each philosopher picks up right fork and the left fork *at the same time*, and then starts eating; after having eaten, the philosopher puts them both back down
- A philosopher could *starve*



# Starvation

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- Even if no deadlock occurs, it may still happen that some processes are not treated fairly
- The situation that processes are perpetually denied access to resources is called *starvation*

- To prove freedom from starvation or other liveness properties, **fairness assumptions** are sometimes needed
- Fairness is concerned with a fair resolution of nondeterminism
- **Weak fairness**: if an action is *continuously enabled*, i.e. never temporarily disabled, then it has to be executed infinitely often
- **Strong fairness**: if an action is *infinitely often enabled*, but not necessarily always, then it has to be executed infinitely often