ID1217 Concurrent Programming
Lecture 2

ROYAL INSTITUTE
OF TECHNOLOGY

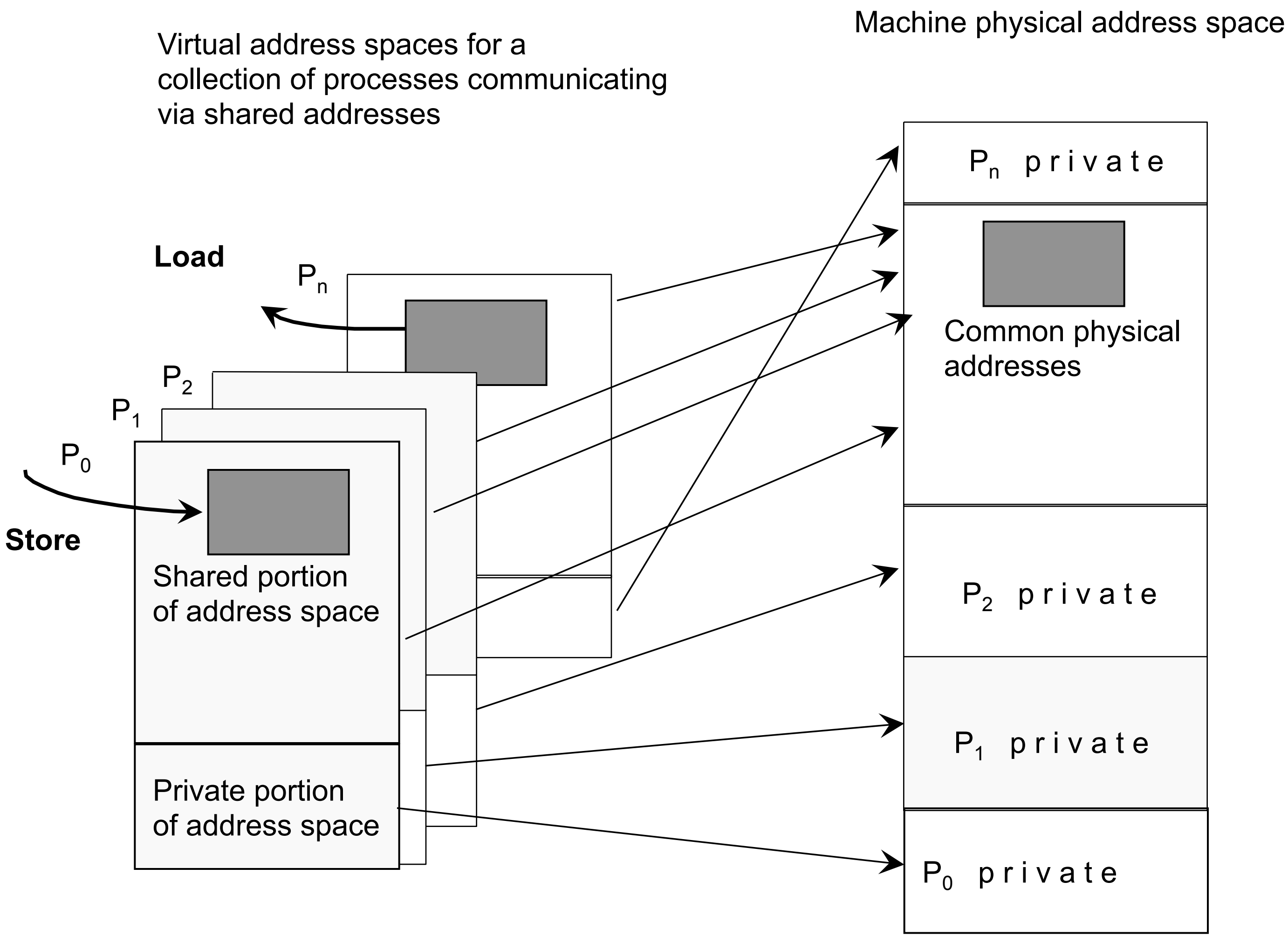
Shared Memory Programming: Processes and Synchronization

Vladimir Vlassov
KTH/EECS

Outline

- Processes
  - Atomic actions
  - Process histories.
  - Interleaving semantics and nondeterminism of concurrent execution.
- Synchronization
  - Atomicity.
  - The await statement.
  - At-Most-Once property.
- Examples of parallelization and synchronization
  - Finding patterns in a file.
  - Find the maximum element in an array.

Shared Address Space Model



Process State. Actions. Process History

ROYAL INSTITUTE OF TECHNOLOGY

- ***Process (thread)*** is an abstract entity that performs tasks assigned to processes
- ***Process state*** is formed of values of variables at a point in time.
- Each process executes a sequence of statements.
- Each statement consists of one or more ***atomic (indivisible) actions*** which transform one state into another
  - Some actions allow processes to communicate with each other
- Sequence of states makes up a process history
- The ***process history*** is a trace of ONE execution.

$$\mathbf{P: Q_0 \xrightarrow{a_1} Q_1 \xrightarrow{a_2} \ldots \xrightarrow{a_m} Q_m}$$

ROYAL INSTITUTE OF TECHNOLOGY

Atomic Actions

- ***Atomic action*** – indivisible sequence of state transitions made atomically
- Fine-grained atomic actions
  - Machine instructions (read, write, swap, etc.) – atomicity is guaranteed by HW
- Coarse-grained atomic actions
  - A sequence of fine-grained atomic actions executed indivisibly (atomically)
    - Internal state transitions are not visible “outside”
    - For example, a critical section of a code
- Notation (to be used further): **< statements >** – a list of statements to be executed atomically.

Interleaving Semantics of Concurrent Execution

- The concurrent execution of several processes can be viewed as **the interleaving of histories of the processes**
  - i.e., the interleaving of sequences of atomic actions of different processes.
- Individual histories:
  - Process 1: $s_0 \to s_1 \to s_2 \to \ldots \to s_n$
  - Process 2: $p_0 \to p_1 \to p_2 \to \ldots \to p_n$
  - Process 3: $q_0 \to q_1 \to q_2 \to \ldots \to q_n$
- Interleaved concurrent histories:
  - Trace 1: $s_0 \to p_0 \to s_1 \to p_1 \to p_2 \to q_0 \to s_2 \to q_1 \to \ldots$
  - Trace 2: $p_0 \to s_0 \to q_0 \to q_1 \to s_1 \to p_1 \to p_2 \to q_2 \to \ldots$

Nondeterminism of Concurrent Execution

- **Nondeterminism**: The behavior of a concurrent program is not reproducible because different interleavings (histories) can be observed on different concurrent executions.
- Reason: **Asynchrony**
  - Each process executes at its own rate (caches misses, page faults, etc.)
  - **Concurrent means ambiguous temporal order**
- A concurrent program of n processes each of m atomic actions can produce $(n \times m)!/(m!)^n$ different histories.
  - For example, $n = 3$, $m = 2$ give **90** different histories.
- Impossible to show the correctness of a program by testing ("run the program and see what happens").

Example of Nondeterminism

- A program:

```
int y = 0; z = 0;
co x = y + z; ||  y = 1; z = 2; oc
```

- Trace 1:

```
x = y{0} + z{0}; y = 1; z = 2;      {x == 0}
```

- Trace 2:

```
y = 1; x = y{1} + z{0}; z = 2;      {x == 1}
```

- Trace 3:

```
y := 1; z := 2; x := y{1} + z{2};  {x == 3}
```

- Trace 4:

```
load y{0} to R1; y := 1; z := 2;
  add z{2} to R1{0}; store R1 to x; {x == 2}
```

Synchronization

- **Synchronization** is a mechanism to delay a process until it may proceed
  - Allows reducing the entire set of possible histories to those which are desirable (correct).
    - To preserve (true) dependences between processes
    - To avoid race conditions if any
    - To coordinate access to shared resources
    - To hide state transitions
- Two kinds of synchronization:
  - **Mutual exclusion**
    - guarantees that only one process at a time accesses a shared resource, i.e. only one process at a time executes its critical section.
  - **Condition synchronization**
    - delays a process until a certain condition is true.

Specifying Synchronization: The Await Statement

ROYAL INSTITUTE OF TECHNOLOGY

- `< await(B) S; >`
  - Wait for **B** to be true, then execute **S** atomically
  - Combines condition synchronization with mutual exclusion
    - Executed as an atomic action
    - **B** is guaranteed to hold when **S** begins
    - **S** is guaranteed to terminate
- `< await(B); >`
  - Wait for a condition **B** to be true.
  - Used to express condition synchronization
- `< S; >`
  - Execute a list of statements **S** atomically (indivisibly).
  - Can be used to express mutual exclusion

Assumptions on Machine Architecture

- RISC architecture
  - Values are manipulated by loading them into registers, operating on them, and storing them back to memory
- **Atomic memory operations (atomic registers)**
  - Values of the basic types are stored in memory elements that are read and written as atomic actions
- Process context
  - Each process has its own set of registers and stack
- All temporaries are stored in private memory
  - Any intermediate results are stored in registers or in process' private memory (on stack)

Registers (Memory Locations)***

- Safe register
  - If read does not overlap write, read returns the value written by the most recent write
  - If read overlaps write, it returns any value (from the range of valid values)
- Regular register
  - If read does not overlap write, the register is safe
  - If read overlaps write, it returns either the old or the new value
- **Atomic register (we assume)**
  - If read does not overlap write, the register is safe, i.e. read returns the value written by the most recent write
  - If read overlaps with write, it returns either the old value or the new value but not newer than the next read

The At-Most-Once Property

ROYAL INSTITUTE OF TECHNOLOGY

- Unnecessary explicit coarse-grained atomicity causes unnecessary overhead and may reduce parallelism.
- **Critical reference** is a reference to a variable which is (can be) changed by another process.
- A statement **`x = e`** appears to be executed atomically when it satisfies the **At-Most-Once (AMO) property**, i.e. if
  - either (a) **`e`** contains at most one critical reference and **`x`** is not referenced by another process;
  - or (b) **`e`** contains no critical references and **`x`** may be read by other processes.

Implication of the AMO Property

`< S; > ≡ S;`

– as long as **S** contains at most one critical reference seeing by other processes,

– In this case, one cannot tell the difference, so **S** will appear to execute atomically w.r.t. to other processes.

`< await(B); > ≡ while (not B) continue;`

– if **B** contains (reads) at most one critical reference

Parallelizing a Sequential Program

- How? Identify independent and dependent tasks, assign tasks to processes, identify shared variables, synchronize processes.
- Data accessed by a process:
  - Read set (rs) – variables that are only read
  - Write set (ws) – variables that are written (and possibly read)
- **Independence**: processes are independent iff the write set of one proc is disjoint from the read and write sets of another proc:

$$\boxed{ws_1 \cap (rs_2 \cup ws_2) = \varnothing \text{ AND } ws_2 \cap (rs_1 \cup ws_1) = \varnothing}$$

Dependencies Between Atomic Actions w.r.t. to a Shared Variable

ROYAL INSTITUTE OF TECHNOLOGY

- Assume two atomic actions access the same variable
- Dependences:
  - **True dependence**: read after write, e.g. `x := 1; a := x;`
  - **Anti dependence**: write after read , e.g. `a := x; x := 1;`
  - **Output dependence**: write after write, e.g. `x : = 1; x := 2;`
  - **Input dependence**: read after read, e.g. `a := x; b := x;`
- If the actions are executed by different processes, all dependencies must be preserved by synchronization
  - Input dependences do not require synchronization
  - Some anti and output dependencies can be **false dependencies** caused by reuse of memory – To avoid, rename (disjoin) variables
  - An output dependence does not need to be preserved (ordered) if the order of writes is not important, e.g. OR-parallelism

Example of Parallelization and Synchronization: Finding Patterns in a File

- Find all instances of a pattern in a file: `grep pattern filename`
- Sequential program:

```
string line;
open the file; read a line of input from the file into line;
while (!EOF) { // EOF is end of file
        look for pattern in line;
        if (pattern is in line) print line;
        read next line from the file into line;
}
```

- Parallelization:
  - Tasks: read a line, compare with the pattern, print if match
  - Apply Producer-Consumer paradigm:
    - Producer reads a line from the file and stores it to a shared buffer
    - Consumer gets a line from the buffer, tests it against pattern, prints if match.

Example (cont'd): How to Synchronize

- True/anti dependence between P and C via the shared buffer.
- Assume a single-slot buffer
  - the buffer provides place for only one string
- Synchronization:
  - **Mutual exclusion**: The buffer is accessed by one process at a time
  - **Condition synchronization**
    - To put a line, Producer waits for the buffer to be empty
    - To get a line, Consumer waits for a buffer to become full
- Let's use two counters:
    - **p** – number of produced lines (stored to the buffer by Producer)
    - **c** – number of consumed (fetched from the buffer by Consumer)
- Synchronization requirement expressed as a predicate:

$$PC: \; c \le p \le c + 1$$

Example (cont'd): Parallel Program

```
// shared variables:
string buf;    // buffer
bool done = false; // termination
int p = 0, c = 0;  // counters
Process Producer { // reads lines
  string line;
  open the file;
  while (true) {
    read a line from the file into line;
    if (EOF) {
        done = true;
        break;
    }
    // wait for buffer to be empty
    < await (p == c); >
    buf = line;
    p++; // signal that buffer is full
  }
};
```

```
Process Consumer { // finds patterns
  string line;
  while (true) {
    // wait for buffer to be full
    // or done to be true
    < await ((p > c) || done); >
     if (p > c) {
      line = buf;
      c++; // signal that buf is empty
     look for pattern in line;
     if (pattern is in line) write line;
    }
    if (done) break;
  }
}
```

Example of Synchronization: Find the Maximum

- Given array $a[1{:}n]$ of positive integers. Find the maximum value m

$$(\forall j : 1 \le j \le n : \; m \ge a[j]) \;\wedge\; (\exists j : 1 \le j \le n : \; m = a[j])$$

  - When program terminates, m is at least as large as every element of a
  - m is one of elements of a
- Sequential program:

```
int m = 0;
for [i = 0 to n-1]
   if (a[i] > m) m = a[i];
```

- How to parallelize? – Examining all elements in parallel
- Parallel program without synchronization:

```
int m = 0;
co [i = 0 to n-1]
   if (a[i] > m) m = a[i];
oc
```

  - Program is incorrect because of the race condition
  - Synchronization is needed

Example (cont'd): Concurrent Program

- First attempt to synchronize: execute cond. updates atomically

```
int m = 0;
co [i = 0 to n-1]
   ⟨ if (a[i] > m) m = a[i]; ⟩ oc
```

  - Not efficient (over-constrained): all the updates are serialized just like in the sequential program but executed in an arbitrary order.
- Observations:
  - Read and test can be executed in parallel for each `i`
  - Updates of `m` require atomicity (mutual exclusion) for serialization
  - Can use second test in critical section to avoid races

Example (cont' d): Solution for Concurrent Program

- Read and test in parallel without mutual exclusion. Those who passed the test, execute conditional update atomically (with mutual exclusion)

```
int m = 0;
co [i = 0 to n-1]
   if (a[i] > m)
      ⟨ if (a[i] > m) m = a[i]; ⟩
oc
```

Lessons Learned

- Synchronization is required whenever processes read and write shared variables (to preserve true, anti, and output dependences)
- Atomicity helps to provide mutual exclusion
- Test followed by an atomic test-and-update is a useful combination for conditional updates
  - Helps to avoid races among concurrent conditional updates that depend on the same condition

Exercise 1: Non-determinism. Possible final values

ROYAL INSTITUTE OF TECHNOLOGY

- Consider the following fragment of a program outline:

```
var x = 1, y = 2, z = 3;
co x = x + 1;
|| y = y + 2;
|| z = x + y;
|| <await (x > 1) x = 0; y = 0; z = 0 >
oc
```

- Assume that atomic actions in the first three arms of the **co** statement are reading and writing individual variables.
- Does the co-statement terminate? What are the possible final values of x, y and z? Explain.

Solution to Exercise 1

```
var x = 1, y = 2, z = 3;
co x = x + 1
|| y = y + 2
|| z = x + y
|| <await (x > 1) x = 0; y = 0; z = 0 >
oc
```

- The possible final values of x, y and z are

  x = = {0}

  y = = {0,2,4}

  z = = {0,1,2,3,4,5,6}

Exercise 2: Await versus If

- Consider the following program fragmet that spawns three threads in the co-statement:

```
int x = 0;
co <await (x != 0) x = x - 2;>
|| <await (x != 0) x = x - 3;>
|| <await (x == 0) x = x + 5;>
oc
```

a) Does the program terminate? If so, what are the possible final values of **`x`**? If not, why not?

b) Suppose the **`await`** statements are changed to **`if`** statements – namely, that **`await`** is replaced by **`if`** and the angle brackets are deleted. Now the program is sure to terminate. What are the possible final values of **`x`**?

Solution to Exercise 2

(a) Yes, it does terminate. The final value of x is zero. The last statement executes first, then the other two in either order.

(b)

```
int x = 0;
co if (x != 0) x = x - 2; // S1
|| if (x != 0) x = x - 3; // S2
|| if (x == 0) x = x + 5; // S3
oc
```

Possible histories and corresponding final values are the following:

S1 and S2 tests fail then S3	x = = 5
S2 test fails; S3; S1	x = = 3
S1 test fails; S3; S2	x = = 2
S3; S1 || S2	x = = {0, 2, 3}

Exercise 3: Intersection of two arrays

- Given integer arrays `a[1:m]` and `b[1:n]`, assume that each array is sorted in ascending order.

(a) Develop an outline of a sequential program to compute the number of values that appear in both `a` and `b`, i.e. the intersection of `a` and `b`.

(b) Develop an outline of a parallel program based on your sequential program.
Use the `co` statement for concurrent execution and the `await` statement for synchronization (if needed).

Possible Solution to Exercise 3 (a)

ROYAL INSTITUTE OF TECHNOLOGY

(a) We can do a linear search in the arrays to compare the elements and find the common ones.

- The following sequential solution is inefficient:

```
int i = 0, j = 0, count = 0;
for (i = 0; i < m; i++)
  for (j = 0; j < n; j++)
    if (a[i] == b[j]) count++;
```

- The outline of a more efficient sequential program:

```
int i = 0, j = 0, count = 0;
while (i < m && j < n) {
   if (a[i] < b[j]) i++;
   else if (a[i] > b[j]) j++;
   else { count++; i++; j++; }
}
```

Possible Solution to Exercise 3 (b)

(a) The outline of a parallel program:

```
int i = 0, j = 0, count = 0, A, B;
while (i < m && j < n) {
   A = b[i]; B = b[j];
   co if (A < B) i++;
   || if (A > B) j++;
   || if (A == B) { count++; i++; j++; }
   oc
}
```

- There is no need of any synchronization because the conditions are disjoint. Only one of them in every iteration will increment the shared variable(s).

Properties of a Program

- A property of a program is an attribute of ALL histories of a program, e.g., correctness.
- Two kinds of properties:
  - **Safety properties state that nothing bad ever happens**
    - A safety property is one in which the program never enters a “bad” state
  - **Liveness properties state that something good eventually happens**
    - A liveness property is one in which the program eventually enters a “good” (desirable) state

Properties of a Program (cont'd)

- **A property can be represented as a conjunction of a safety property and a liveness property**
- For example:
  - Property: A message sent is always delivered (exactly once)
  - Safety: A message sent is delivered at most once
  - Liveness: A message sent is delivered at least once

Examples of Safety and Liveness Properties

- Safety properties:
  - Partial correctness
    - The final state is correct, assuming that the program terminates
  - Mutual exclusion of critical sections
    - “Bad” when more than one proc. are in critical sessions
  - Absence of deadlocks (deadlock-freedom)
    - A set of processes is deadlocked when each process in the set is waiting for an event which can only be caused by another process in that set.
- Liveness properties:
  - Termination
    - Every history (trace) is finite.
  - Eventually enter a critical section (if any)
- Total correctness combines termination and partial correctness
  - A program always terminates with a correct answer

Proving Properties

Three main approaches

1. Testing or debugging
   - Run and see what happens
   - Limited to considered cases
2. Operational reasoning
   - "Exhaustive case analysis"
   - Considers enormous number of histories: $n{\cdot}m!/(m!)^n$
   - Helps in development
3. **Assertional reasoning**
   - Based on axiomatic semantics: axioms, inference rules, assertions
   - Work is proportional to the number of atomic actions