Programming Paradigms

Lecture 16:

Concurrency (Part 1)

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Wake-up Exercise

What does this Java code print?

```
class Warmup {
  static boolean flag = false;
  static void raiseFlag() {
    flag = true;
  }
  public static void main(String[] args)
      throws Exception {
    ForkJoinPool.commonPool()
      .execute(Warmup::raiseFlag);
    while (!flag) {};
    System.out.println(flag);
  }
}
```

https://ilias3.uni-stuttgart.de/vote/0ZT9

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      .execute(Warmup::raiseFlag);
    while (!flag) {};
    System.out.println(flag);
  }
}
```

`raiseFlag`: executed in concurrent thread

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}
```

Shared variable accessed by two threads

Wake-up Exercise

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      .execute(Warmup::raiseFlag);
    while (!flag) {};
    System.out.println(flag);
  }
}
```

Problem: No synchronization. Hence, main thread may read old value

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Wake-up Exercise

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      .execute(Warmup::raiseFlag);
    while (!flag) {};
    System.out.println(flag);
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}
```

Code may hang forever, print `true`, or print `false`!

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Overview

- Introduction
- Concurrent Programming Fundamentals
- Implementing Synchronization
- Language-level Constructs

Motivation

Why do we care about concurrency?

- To capture the logical structure of a problem
  - Inheritently concurrent problems, e.g., server handling multiple requests
- To exploit parallel hardware for speed
  - Since around 2005: Multi-core processors are the norm
- To cope with physical distribution
  - Local or global groups of interacting machines

Terminology

- **Concurrent**
  - Two or more running tasks whose execution may be at some unpredictable point
- **Parallel**
  - Two or more tasks are actively executing at the same time
  - Requires multiple processor cores
- **Distributed**
  - Physically separated processors

Levels of Parallelism

- **Signals propagating through circuits and gates**
- **Instruction-level parallelism**
  - E.g., load from memory while another instruction executes
- **Vector parallelism**
  - E.g., GPUs execute a single instruction on a vector of data
- **Thread-level parallelism**

Levels of Parallelism

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- **Instruction-level parallelism**
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- **Thread-level parallelism**

Handled implicitly by hardware

Levels of Parallelism

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  - E.g., GPUs execute a single instruction on a vector of data
- **Thread-level parallelism**

Specified by programmer in PL

Example: Independent Tasks

```
// Task Parallel Library in C#
Parallel.For(0, 100, i => {
  A[i] = foo(A[i]);
});
```

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Array of data

Function that updates each element independently

Example: Independent Tasks

```
// Task Parallel Library in C#
Parallel.For(0, 100, i => {
  A[i] = foo(A[i]);
});
```

Array of data

Function that updates each element independently

- No need to synchronize tasks
- Uses as many cores as possible (up to 100)

Example: Dependent Tasks

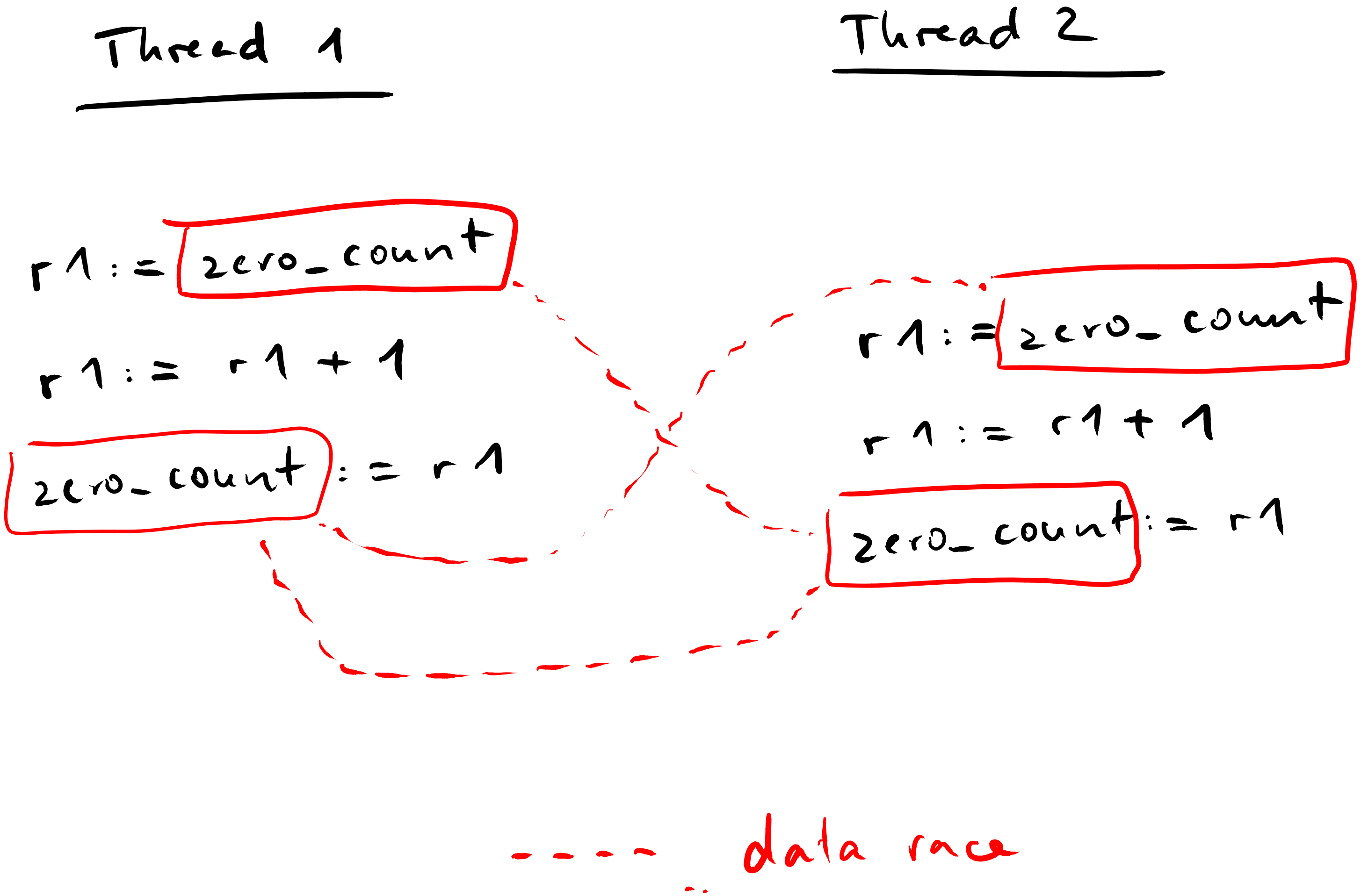
```
// As before, but foo now is:
int zero_count;
public static int foo(int n) {
  int rtn = n - 1;
  if (rtn == 0) zero_count++;
  return rtn;
}
```

Example: Dependent Tasks

```
// As before, but foo now is:
int zero_count;
public static int foo(int n) {
  int rtn = n - 1;
  if (rtn == 0) zero_count++;
  return rtn;
}
```

Count how many zeros written to the array

Data Race


Thread 1
r1 := zero_count
r1 := r1 + 1
zero_count := r1
Thread 2
r1 := zero_count
r1 := r1 + 1
zero_count := r1
---- data race

Data Races

- **Definition of data race**
  - Two accesses to the same shared memory location
  - At least one access is a write
  - Ordering of accesses is non-deterministic

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Processes, Threads, Tasks

- **Process**: Operating system construct that may execute threads
- **Thread**: Active entity that the programmer thinks of as running concurrently with other threads
- **Task**: Unit of work that must be performed by some thread

Processes, Threads, Tasks

OS level

- **Process**: Operating system construct that may execute threads
- **Thread**: Active entity that the programmer thinks of as running concurrently with other threads
- **Task**: Unit of work that must be performed by some thread

PL level

Logical level

Processes, Threads, Tasks

- **Process**: Operating system construct that may execute threads
- **Thread**: Active entity that the programmer thinks of as running concurrently with other threads
- **Task**: Unit of work that must be performed by some thread
- Terminology differs across PLs and systems
- More general than, e.g., Java's "threads"

Communication

- **Constructs to pass information between threads**
  - Shared memory: Some variables accessible by multiple threads
  - Message passing: No shared state, but threads send messages to each other
  - Some PLs provide both

Synchronization

- **Mechanisms to control relative order of operations in different threads**
- **Explicit in shared-memory model**
  - Must synchronize to ensure that variable read sees newest value stored in the variable
- **Implicit in message-passing model**
  - Sender receives message after it has been sent

Spinning vs. Blocking

- **Two forms of synchronization**
- **Spinning (also: busy-waiting)**
  - Thread re-evaluates some condition until it becomes true (because of some other thread)
- **Blocking**
  - Waiting threads stops computation until some condition becomes true
  - Scheduler reactives the thread

Examples

	Shared memory	Message passing	Distributed computing
Language	Java, C#, C/C++	Go	Erlang
Extension	OpenMP		Remote procedure call
Library	pthreads, Windows threads	MPI	Internet libraries

Thread Creation Syntax

- **How to create a thread of execution?**
- **Five answers in popular PLs**
  - Co-begin
  - Parallel loops
  - Launch-at-elaboration
  - Fork (with optional join)
  - Implicit receipt

Co-begin

- Compound statement where all statements are executed concurrently
- Example (pseudo-code):

```
co-begin
  stmt_1
  stmt_2
  ...
  stmt_n
end
```

Example: C with OpenMP

```
#pragma omp sections
{
#   pragma omp section
    { printf("thread 1 here\n"); }

#   pragma omp section
    { printf("thread 2 here\n"); }
}
```

Example: C with OpenMP

```
#pragma omp sections
{
#   pragma omp section
    { printf("thread 1 here\n"); }

#   pragma omp section
    { printf("thread 2 here\n"); }
}
```

Pragmas: Compiler directives

(# sign must be in first column)

Parallel Loops

- Loop whose **iterations execute concurrently** instead of sequentially
- Ex. 1: C with OpenMP

```
#pragma omp parallel for
for (int i = 0; i < 3; i++) {
  printf("thread %d here\n", i);
}
```

- Ex. 2: C# with Task Parallel Library

```
Parallel.For(0, 3, i => {
  Console.WriteLine("Thread " + i + " here");
});
```

Synchronization in Parallel Loops

- **What about data races in parallel loops?**
- **Most PLs: Developer's responsibility**
- **Some PLs: Implicit synchronization**
  - E.g., `forall` loops in Fortran 95: Synchronization on every assignment
    - All reads on right-hand side are before writes on the left-hand side

Example: Fortran 95

```
forall (i=1:n-1)
    A(i) = B(i) + C(i)
    A(i+1) = A(i) + A(i+1)
end forall
```

Example: Fortran 95

```
forall (i=1:n-1)
    A(i) = B(i) + C(i)
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end forall
```

Reads and writes of array elements

Example: Fortran 95

Assignments: Implicit synchronization points

```
forall (i=1:n-1)
    A(i) = B(i) + C(i)
    A(i+1) = A(i) + A(i+1)
end forall
```

Reads and writes of array elements

Example: Fortran 95

At first, all threads read from `B` and `C`

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forall (i=1:n-1)
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```

At first, all threads read from `B` and `C`

Then, all writes to `A(i)` happen

Example: Fortran 95

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forall (i=1:n-1)
    A(i) = B(i) + C(i)
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At first, all threads read from `B` and `C`

Then, all writes to `A(i)` happen

Next, all threads read the just written values from `A`

Example: Fortran 95

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forall (i=1:n-1)
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    A(i+1) = A(i) + A(i+1)
end forall
```

At first, all threads read from `B` and `C`

Then, all writes to `A(i)` happen

Next, all threads read the just written values from `A`

Finally, the threads write updated values to `A(i+1)`

Quiz: Parallel Loops

```
forall (i=1:n-1)
    A(i) = B(i) + C(i)
    A(i+1) = A(i) + A(i+1)
end forall
```

What is the value of `A` after executing the loop with these initial values:

- A is `0, 0, 0`
- B is `1, 2, 3`
- C is `3, 2, 3`
- n is `3`

(Note: Arrays indices starts at 1 in Fortran)

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T1	T2
i = 1	i = 2
1 + 3 = 4	2 + 2 = 4
A(1) = 4	A(2) = 4
4 + 4 = 8	4 + 0 = 4
A(2) = 8	A(3) = 4

All threads wait for each other

→ A = [4, 8, 4]

Data Sharing in Parallel Loops

- **Some PLs: Can specify which variables are shared among threads**
- **E.g., OpenMP**
  - Shared data: All threads access same data
  - Private data: Each thread has its own copy
  - Reduction: Reduce a private variable across all threads at end of loop

Example: C with OpenMP

```
double A[N];
double sum = 0;

#pragma omp parallel for \
    default(shared) reduction(+:sum)
for (int i = 0; i < N; i++) {
  sum += A[i];
}
printf("sum: %f\n", sum);
```

Example: C with OpenMP

All variables (except for `i`) are shared by default

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double A[N];
double sum = 0;

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Example: C with OpenMP

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double A[N];
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  sum += A[i];
}
printf("sum: %f\n", sum);
```

All variables (except for `i`) are shared by default

Exception from default:

- Each thread has private copy of `sum` initialized before entering loop
- At end of loop, combine all copies with +

Launch-at-Elaboration

- Associate a thread with a specific subroutine
- Start thread when subroutine gets called
- At end of subroutine, wait for thread to complete
- Thread shares local variables with the subroutine

Example: Ada

```
procedure P is
  task T is
    Put_Line ("In task T");
  end T;
begin
  Put_Line ("In default task of P");
end P;
```

Example: Ada

“Task” is Ada’s terminology for “thread”

```
procedure P is
  task T is
    Put_Line ("In task T");
  end T;
begin
  Put_Line ("In default task of P");
end P;
```

Runs concurrently with (implicit) task of `P`

Fork/Join

- **Fork: Explicit creation of a thread**
- **Join: Wait for a previously forked thread to terminate**

Example: Java

```
class ImageRenderer extends Thread {
  ImageRenderer(someArg) { ... }
  public void run() {
    // code run by the thread
  }
}

// ...

ImageRenderer rend = new ImageRenderer(...);
rend.start();
// ...
rend.join();
```

Example: Java

Threads: Subclasses of `Thread`

```
class ImageRenderer extends Thread {
  ImageRenderer(someArg) { ... }
  public void run() {
    // code run by the thread
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ImageRenderer rend = new ImageRenderer(...);
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Example: Java

Threads: Subclasses of `Thread`

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```

Share values with thread via arguments

Example: Java

Threads: Subclasses of `Thread`

```
class ImageRenderer extends Thread {
  ImageRenderer(someArg) { ... }
  public void run() {
    // code run by the thread
  }
}

// ...

ImageRenderer rend = new ImageRenderer(...);
rend.start();
// ...
rend.join();
```

Share values with thread via arguments

Lifetime of thread

Example: C#

```
class ImageRenderer {
  public void Render() {
    // code to be run by the thread
  }
}

// ...


ImageRenderer rendObj = new ImageRenderer();
Thread rend = new Thread(
    new ThreadStart(rendObj.Render));
rend.Start();
// ...
rend.Join();
```

Example: C#

```
class ImageRenderer {
  public void Render() {
    // code to be run by the thread
  }
}

// ...

ImageRenderer rendObj = new ImageRenderer();
Thread rend = new Thread(
    new ThreadStart(rendObj.Render));
rend.Start();
// ...
rend.Join();
```

Just a normal method ...

... turned into a thread

Thread Pools

- **Goal: Separate tasks to execute from how they are executed in threads**
- **Thread pool: Set of (idle) threads that can execute tasks**
  - Reduces cost of creating and starting threads by reusing them
  - Let pool implementation decide how exactly to schedule tasks for execution

Example: Java

```
class ImageRenderer implements Runnable {
  ImageRenderer(someArg) { ... }
  public void run() {
    // code run by this task
  }
}

// ...

Executor pool = Executors.newFixedThreadPool(4);
pool.execute(new ImageRenderer(...));
```

Example: Java

```
class ImageRenderer implements Runnable {
  ImageRenderer(someArg) { ... }
  public void run() {
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}

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Not a `Thread` anymore, but only a `Runnable`

Example: Java

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Not a `Thread` anymore, but only a `Runnable`

Pool with 4 threads used to execute any number of threads

Spawn and Sync in Cilk

- **Extension of C language**
- **Programmer expresses tasks and their dependencies**
  - `spawn` calls a function to be executed as a logically concurrent task
  - `sync` joins all tasks spawned by the calling task
- **Scheduler assigns tasks to processor cores through work stealing**

Example: Fibonacci

Sequential implementation:

```
int fib (int n) {
  if (n < 2) return 1;
  else {
    int res = 0;
    res += fib (n - 1);
    res += fib (n - 2);

    return res;
  }
}
```

Example: Fibonacci

Parallel implementation with Cilk:

```
cilk int fib (int n) {
  if (n < 2) return 1;
  else {
    int res = 0;
    res += spawn fib (n − 1);
    res += spawn fib (n − 2);
    sync;
    return res;
  }
}
```

Example: Fibonacci

Parallel implementation with Cilk:

```
cilk int fib (int n) {
  if (n < 2) return 1;
  else {
    int res = 0;
    res += spawn fib (n - 1);
    res += spawn fib (n - 2);
    sync;
    return res;
  }
}
```

Execute in parallel with parent

Wait until children have returned

Implicit Receipt

- **In remote procedure call (RPC)-based systems**
- **Create thread in response to an incoming request from some other address space**
  - E.g., from another machine

Quiz: Concurrency

Which of the following sentences are true?

- Concurrency means different machines perform computations at the same time.
- In OpenMP's parallel loops, all data is private to the respective thread.
- A thread in a thread pool may execute any number of tasks.
- The scheduler re-actives a busy-waiting thread.

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Quiz: Concurrency

Which of the following sentences are true?

- ~~Concurrency means different machines perform computations at the same time.~~
- ~~In OpenMP's parallel loops, all data is private to the respective thread.~~
- A thread in a thread pool may execute any number of tasks.
- ~~The scheduler re-actives a busy-waiting thread.~~

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