Programming Paradigms

Concurrency (Part 1)

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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**

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Handled implicitly by hardware

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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

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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

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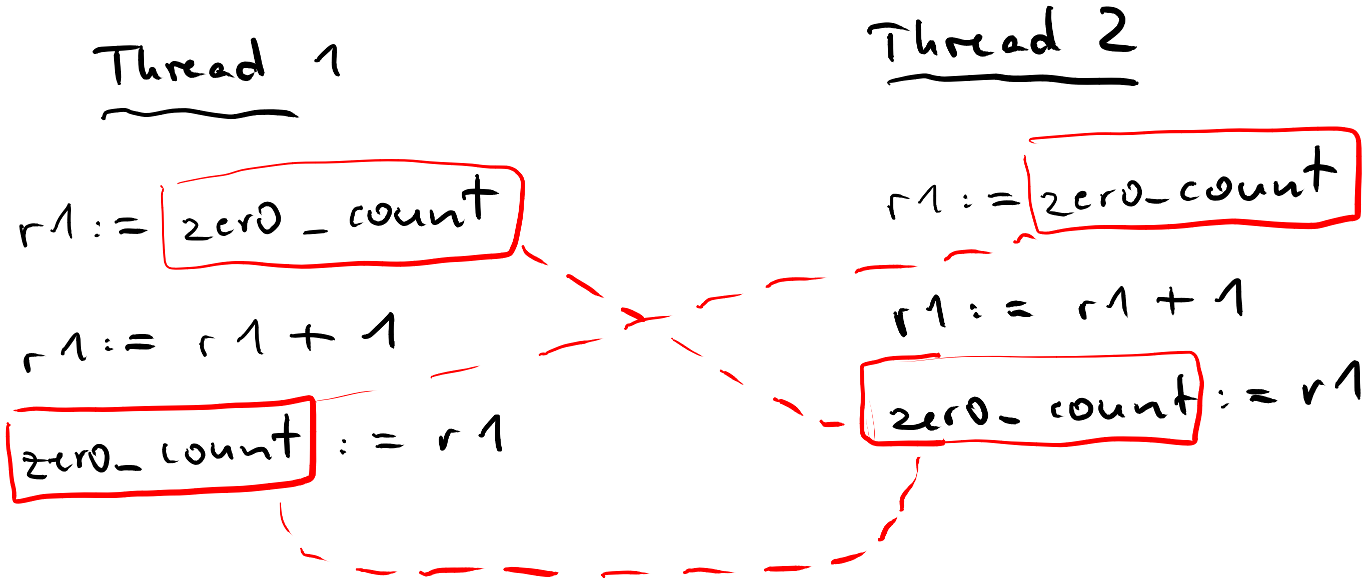
```

Count how many zeros written to the array

Problem : 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 races

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

Another Example

```
// code to transfer money between accounts
// written in a toy language
fun transfer(amount, account_from, account_to) {
  if (account_from.balance < amount) return NOPE;
  atomic {
    account_to.balance += amount;
    account_from.balance -= amount;
  }
  return YEP;
}
```

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Ensures that code block is executed atomically, i.e., no other thread executes it at the same time

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```

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Quiz: Could a program invoking `transfer` multiple times concurrently have a data race?

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    account_to.balance += amount;
    account_from.balance -= amount;
  }
  return YEP;
}
```

Yes, there still is a data race:

Concurrent and unsynchronized read

and write of `account_from.balance`

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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

PL level

- **Task**: Unit of work that must be performed by some thread

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

Quiz: Terminology

Which of the following sentences are true?

- Concurrency means different machines perform computations at the same time.
- A data race can occur only when two threads execute concurrently.
- Instruction-level parallelism should be avoided to ensure correctness.
- In PLs with message passing, messages typically exchange pointers to shared memory.

Quiz: Terminology

Which of the following sentences are true?

- ~~Concurrency means different machines perform computations at the same time.~~
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- ~~In PLs with message passing, messages typically exchange pointers to shared memory.~~

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

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}
```

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

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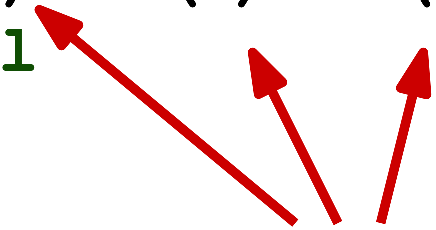

Reads and writes of array elements

Example: Fortran 95

Assignments: Implicit synchronization points

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

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

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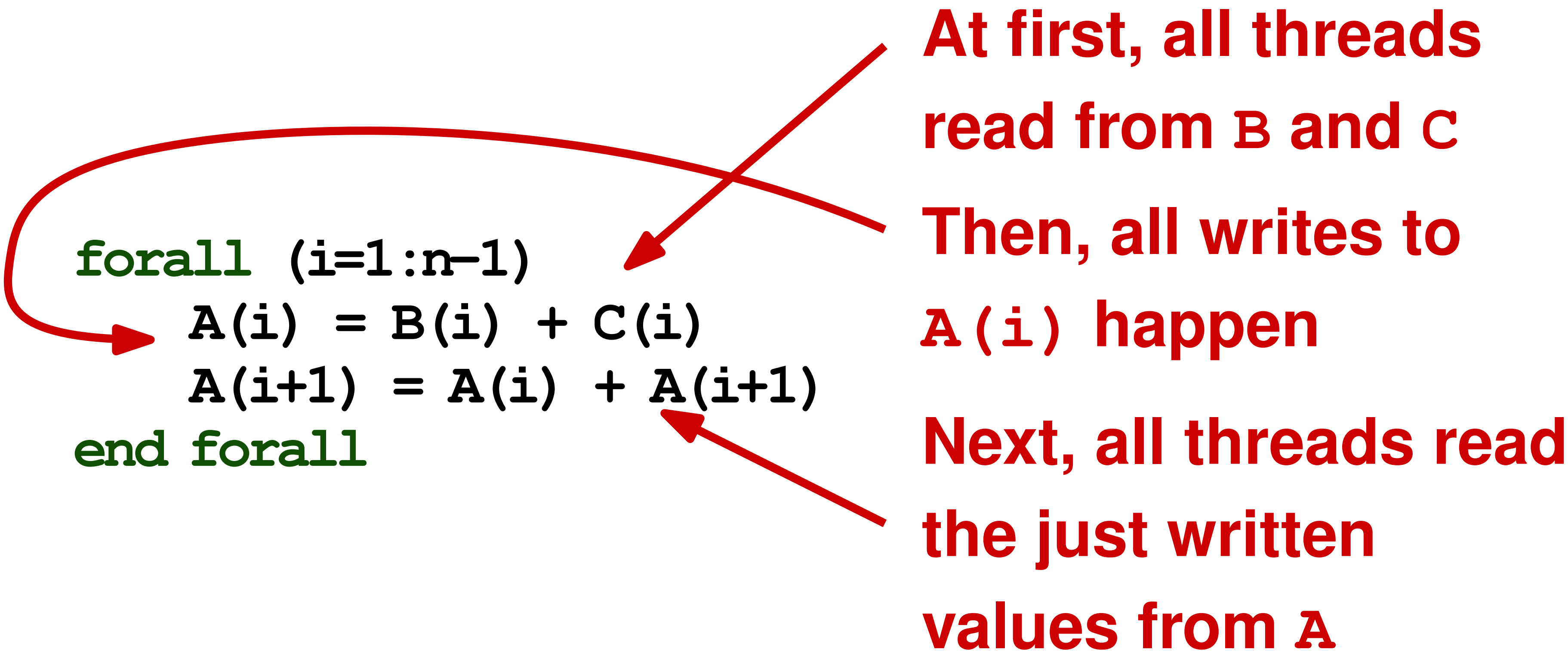

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Then, all writes to `A(i)` happen

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

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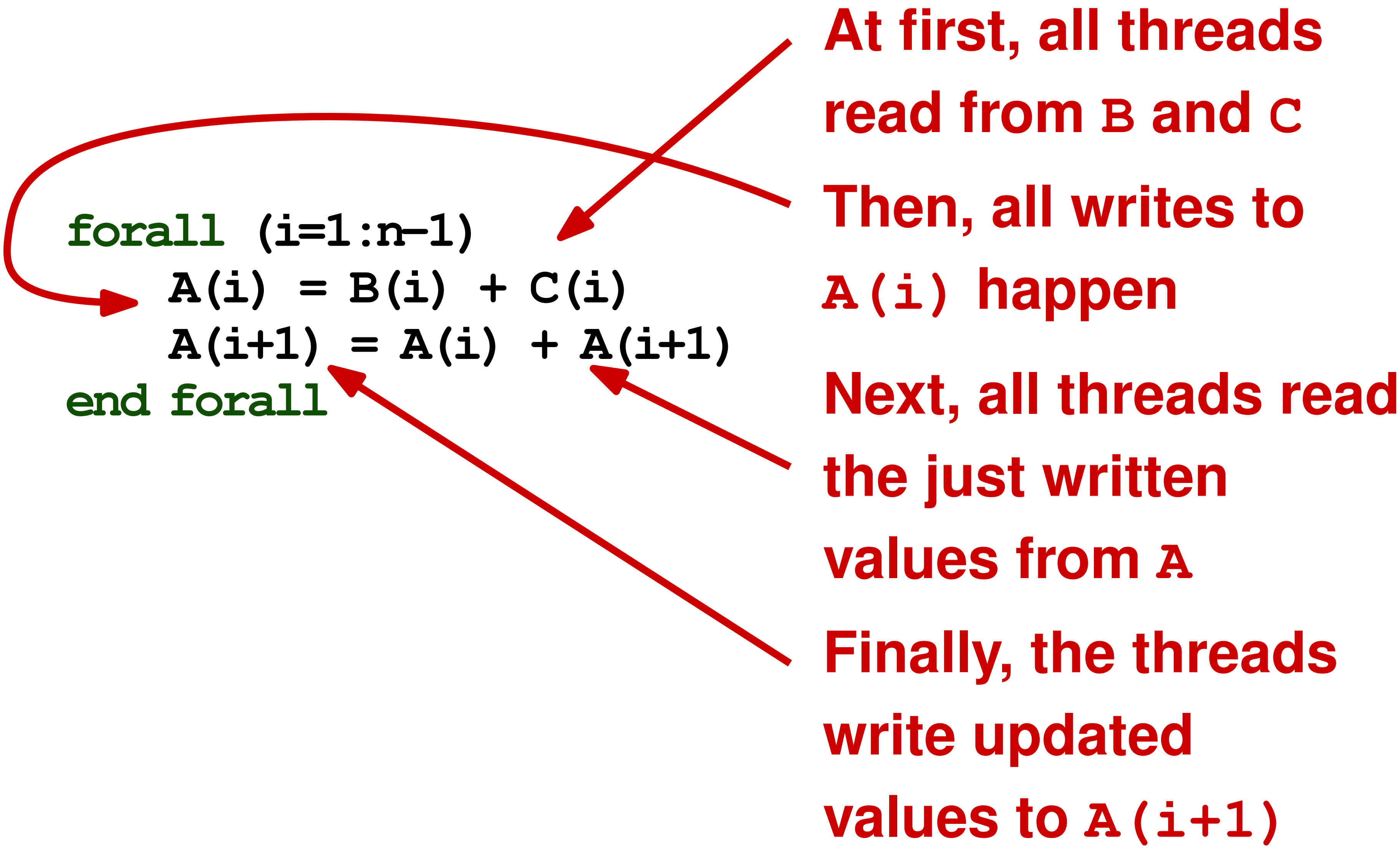

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```

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`

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 `[2, 2, 3]`
- C is `[3, 1, 2]`
- n is `3`

(Note: Arrays indices start at 1 in Fortran)

Thread 1	Thread 2
i := 1	i := 2
2 + 3 gives 5	2 + 1 gives 3
A(1) := 5	A(2) := 3
5 + 3 gives 8	3 + 0 gives 3
A(2) = 8	A(3) = 3

All threads wait for each other

→ A is [5, 8, 3]

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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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”

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procedure P is
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Runs concurrently with (implicit) task of `P`