ETH Zürich

Chair of Software Engineering

Concepts of Concurrent Computation

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Lecture 9: Review of Concurrent Languages

Today's lecture

In this lecture you will learn about:

- Types of computer architectures for concurrency
- How to classify various approaches to concurrency in programming languages
- A number of message passing approaches to concurrency: Ada, Polyphonic C#, Erlang (Actor model), Message passing interface (MPI)
- A number of shared memory approaches to concurrency: X10, OpenMP, Linda (Coordination languages), Cilk

Computer architectures for concurrency

Types of concurrent computation

- *Flynn's taxonomy*: classification of computer architectures
- Counts the number of current instruction/data streams

	Single Instruction	**Multiple Instruction**
Single Data	SISD	(uncommon)
Multiple Data	SIMD	MIMD

- **SISD**: No parallelism (uniprocessor)
- **SIMD**: Vector processor, GPU
- **MIMD**: Multiprocessing (predominant today)

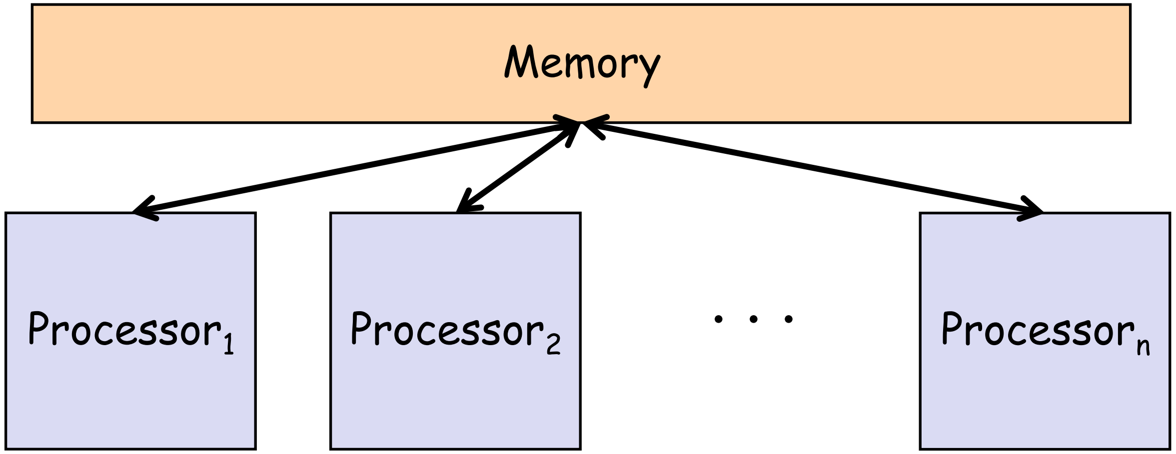
MIMD: subclassification

- **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 the manager

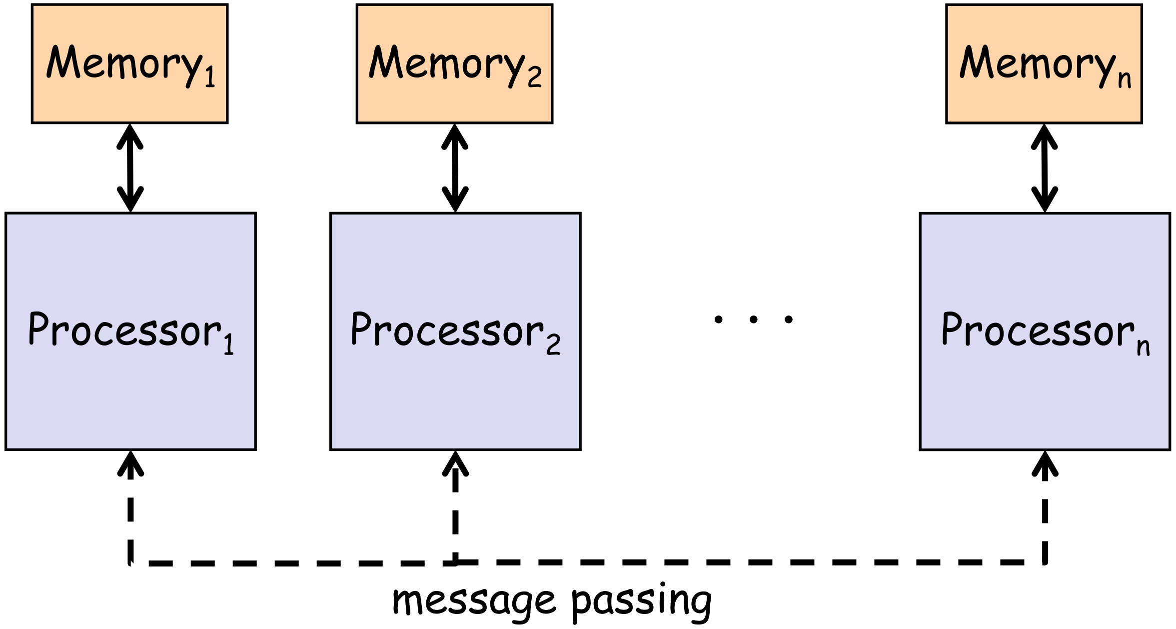
Shared memory model

- All processors share a common memory
- Processes communicate by reading and writing shared variables (*shared memory communication*)



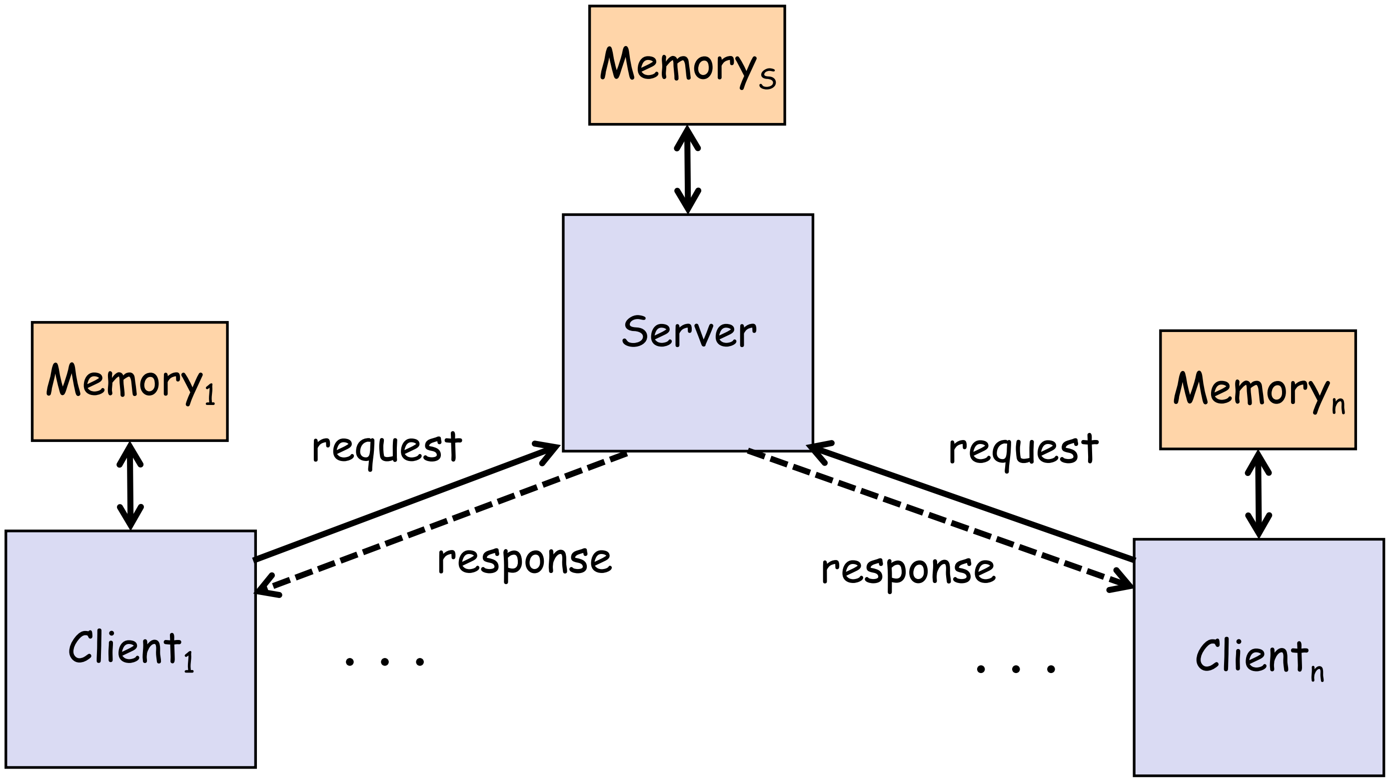
Distributed memory model

- Each processor has its own local memory, which is inaccessible to others
- Processes communicate by sending messages (*message-passing communiction*)
- Common: SPMD architecture



Client-server model

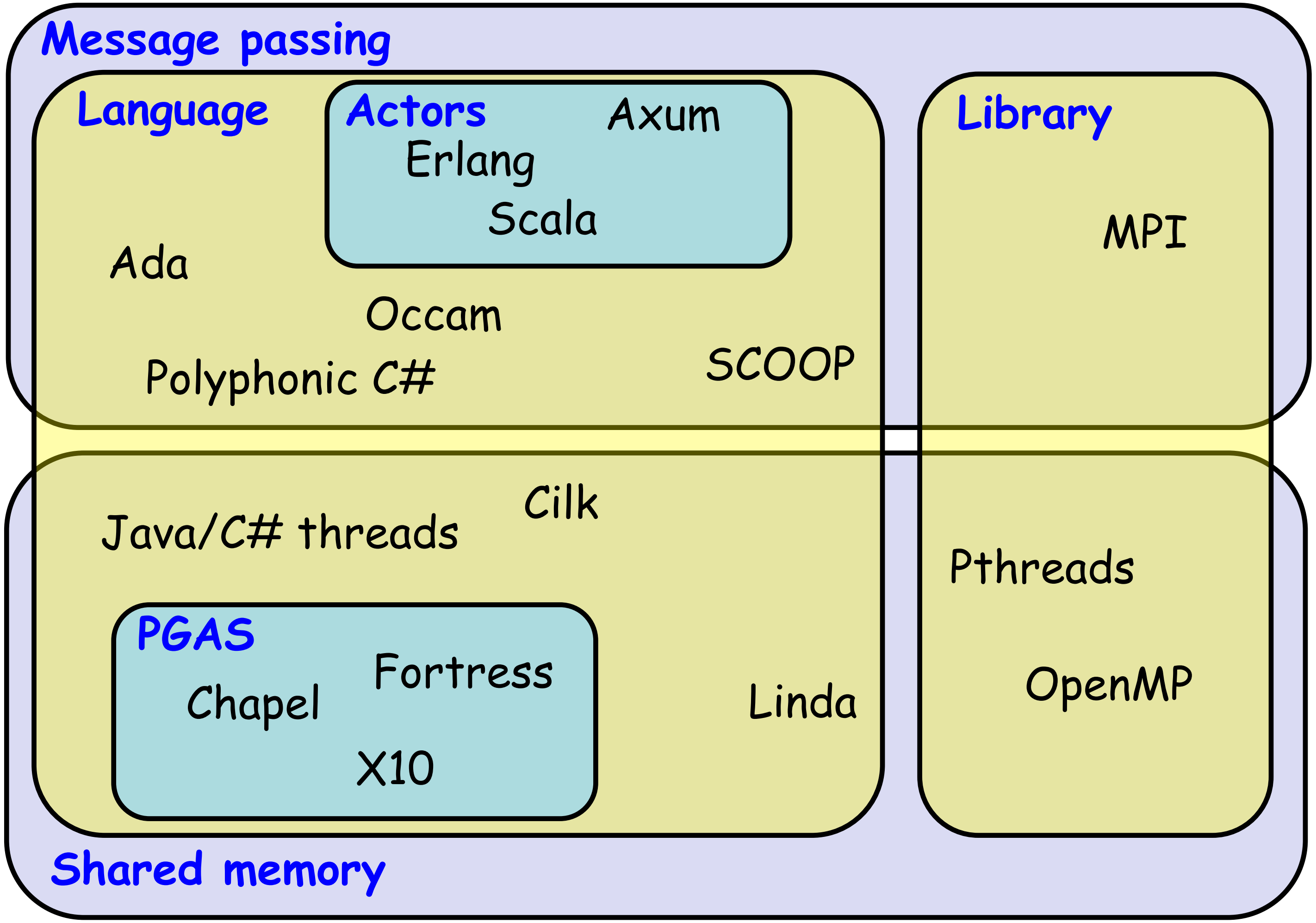
- The *client-server model* is a specific case of distributed model
- Example: World-wide web



Classifying approaches to concurrency

Concurrent languages

- Developers today have the choice among a multitude of different approaches to concurrent programming



Message passing

Language

Actors

Axum

Erlang

Scala

Ada

Occam

Polyphonic C#

SCOOP

Library

MPI

Cilk

Java/C# threads

Pthreads

PGAS

Fortress

Chapel

X10

Linda

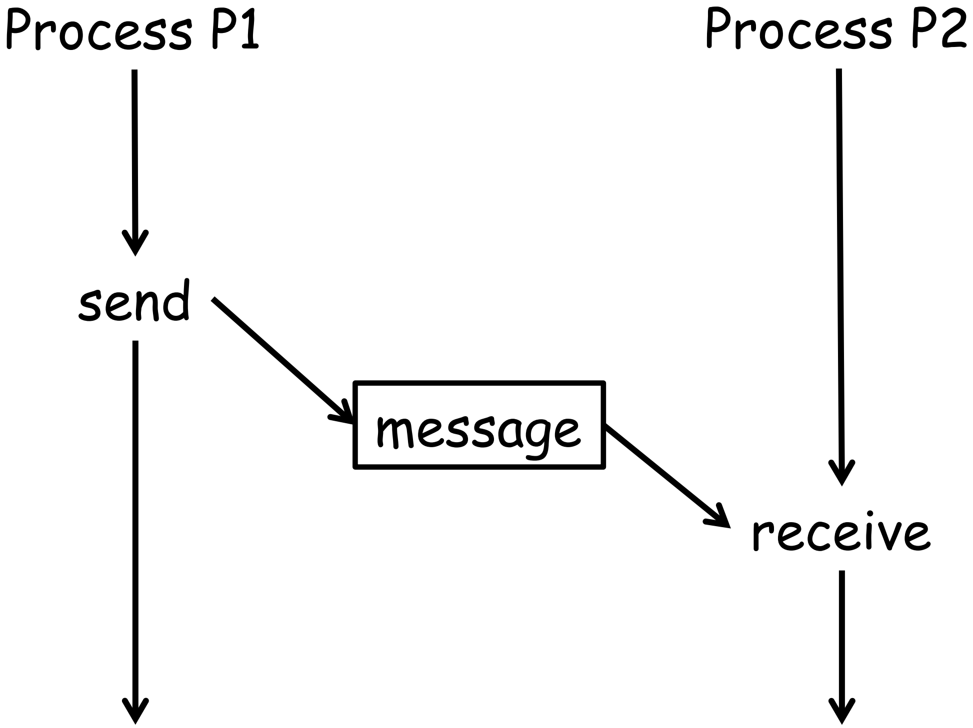
OpenMP

Shared memory

Message passing approaches

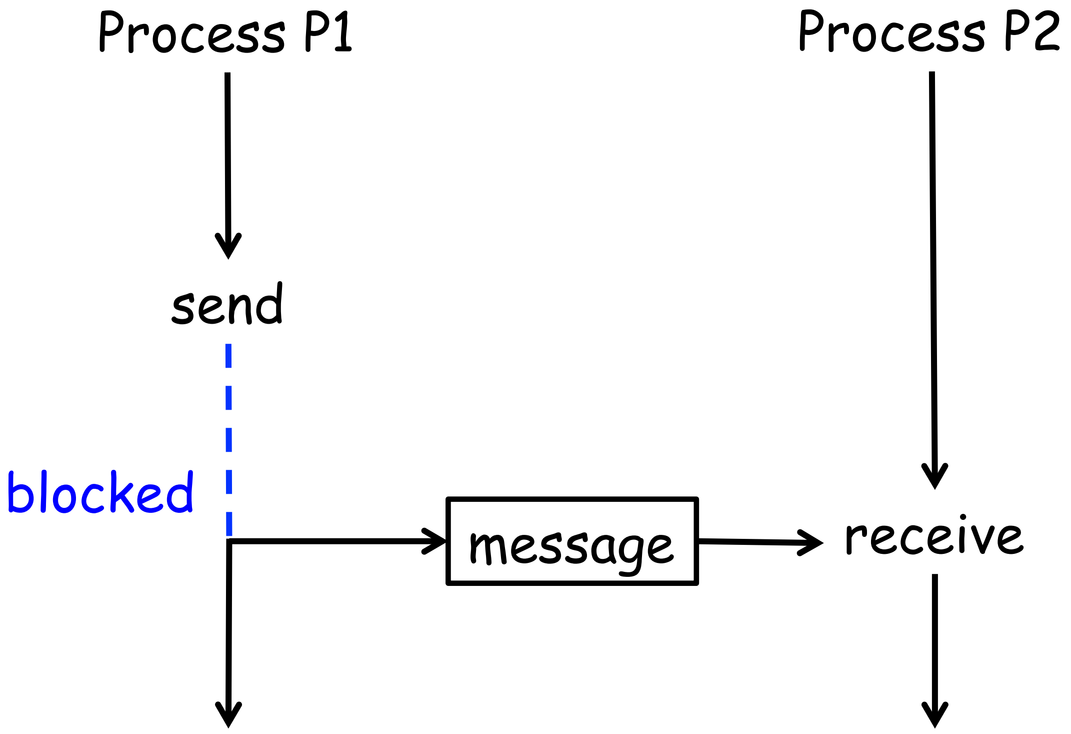
Asynchronous communication

- *Asynchronous*: the sender sends a message and continues, regardless of whether the message has been received
- Requires buffer space
- **Analogy**: Email



Synchronous communication

- *Synchronous*: the sender blocks until the receiver is ready to receive the message
- **Analogy**: Phone call



Ada

Ada

- Object-oriented language, influenced by Pascal, developed from 1975 by US Department of Defence, standards: Ada83, Ada95, Ada 2005
- Design goals: highly reliable systems, reusable components, concurrency part of the language
- Named after Ada Lovelace (1815–1852), “the first computer programmer”
- Supports concurrent execution via *tasks*, which can have *entries* for synchronous message-passing communication
- Ada also offers shared memory synchronization via *protected objects*, a monitor-like mechanism where condition variables are replaced with *guards*

Ada Tasks

- Tasks are declared within procedures
- Two parts: task specification, task implementation
- Tasks are activated when the procedure starts executing

```
procedure SimpleProc is
     task type SimpleTask;

     task body SimpleTask is
     begin
          ...
     end SimpleTask;

     taskA, taskB: SimpleTask;
begin
     null;
end SimpleProc;
```

Process communication: Rendezvous (1)

- Uses synchronous communication, called the "rendezvous"
- Entry points (declared in the type declaration) specify the actions a task can synchronize on

```
task type SimpleTask is
    entry MyEntry;
end SimpleTask;
```

Process communication: Rendezvous (2)

- **accept**-statements (within the task body) indicate program points where rendezvous can take place
- Clients invoke an entry point to initiate a rendezvous, and wait for the accepting task to reach a corresponding entry point

```
task body SimpleTask is
begin
    ...
    accept MyEntry do
       -- body of rendezvous
    end MyEntry;
    ...
end SimpleTask;
```

```
declare
    T: SimpleTask;
begin
    ...
    T.MyEntry;
    -- wait until T reaches MyEntry
    ...
end SimpleTask;
```

- Upon establishing a rendezvous, the client waits for the accepting task to execute the body of the rendezvous and resumes afterward

Process communication: Rendezvous (3)

- Entry points can have parameters to pass on values

```
accept append(x : in integer) do
   ...
end append;
```

```
buffer.append(item);
```

- **select**-statement allows for waiting for multiple entries
- Within a **select**, alternatives may be guarded by boolean expressions
- Only if the guard evaluates to true the **accept**-statement is permitted

```
select
  when count < n =>
     accept append(x : in integer) do
       ...
     end append;
or
  when ...
```

Example: Producer-Consumer problem in Ada

```
task body Buffer is
   count, in, out: integer := 0;
   buff: array(0..n-1) of integer;
begin
    loop
       select
           when count < n =>
              accept append(x : in integer) do
                  buff(in) := x;
              end append;
           in := (in – 1) mod n; count := count + 1;
       or
           when count > 0 =>
              accept remove(y : out integer) do
                  y := buff(out);
              end remove;
           out := (out + 1) mod n; count := count – 1;
       end select;
    end loop;
end buffer;
```

Protected objects

- Monitor-like concept:
  - All data private
  - Exports only procedures, functions, and entries
- *Functions* may only read data, therefore multiple function calls may be active on the same object
- *Procedures* and *entries* may read and write data, and exclude other procedures and functions
- Invocation of entries with *guards*, similar to Hoare's *conditional critical regions*

Conditional critical regions

- Conditional critical regions provide condition synchronization without condition variables
- If S is a critical region for variable x, then the following is a conditional critical region with guard B:

  region x **when** B **do** S

  - If a process wants to enter a conditional critical region, it must obtain the mutex lock or is queued otherwise.
  - When the lock is acquired, the boolean expression B is tested. If B evaluates to true, the process proceeds into the critical region. Otherwise it releases the lock and is queued. Upon re-acquisition of the lock, the process must retest B.

Example: Protected objects

```
protected type Semaphore is
    entry Down;
    procedure Up;
    function Get_Count return Natural;
  private
    Count: Natural := 0;
  end Semaphore;

protected body Semaphore is
    entry Down when Count > 0 is
    begin
      Count := Count - 1;
    end Down;
    procedure Up is
    begin
      Count := Count + 1;
    end Up;
    function Get_Count return Natural is
    begin
      return Count;
    end Count;
end Semaphore;
```

Ada: Discussion

- One of the first languages to introduce high-level concurrency constructs into the language
- Both message passing and shared memory concepts available: good to fit the approach to the problem at hand and performance requirements
- Ada is still actively developed, next standard Ada 2012

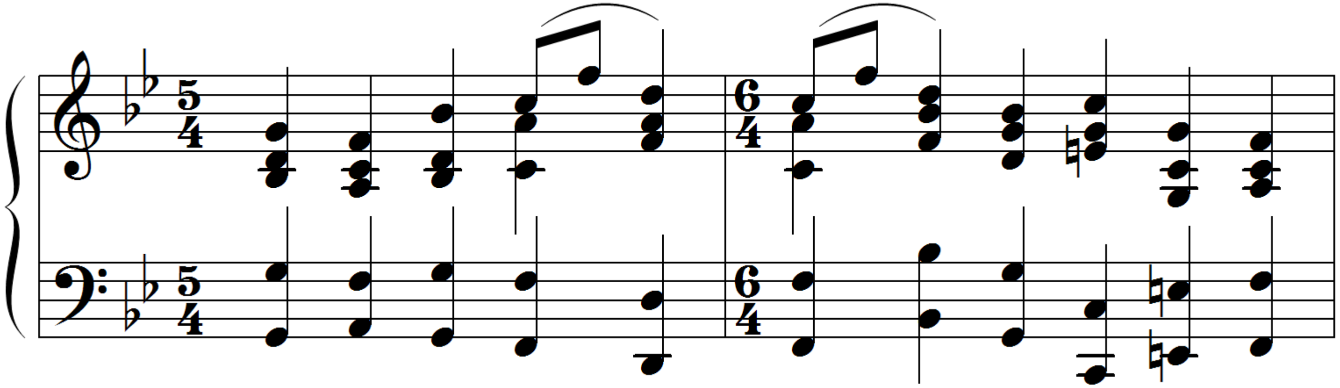
Polyphonic C#

(Based on slides by C.A. Furia)

Polyphonic C#

- Polyphonic C# is an extension of C# with a few high-level primitives for concurrency, appeared in 2004
  - Based on join calculus (Fournet & Gonthier, 1996)
  - Taken up by Microsoft's Cω project
  - JoinJava is a similar extension for Java
- Based on two basic notions
  - Asynchronous methods
  - Chords

(M. Mussorgsky, Pictures at an exhibition)



Asynchronous methods

- Calls to asynchronous methods return immediately without returning any result:
  - The callee is scheduled for execution in a different thread
  - Similar to sending a message or raising an event
  - Declared using **async** keyword instead of **void**

```
public async startComputation () {
    // computation
}
```

- Aynchronous methods do not return any value

Chords: syntax

A *chord* extends the notion of a method definition:

- The signature of a chord is a collection of (traditional) method declarations joined by &
- The body of a chord is all similar to the body of a traditional method

```
public String get() & public async put(String i) {
        return i;
}
```

- Within a chord at most one method can be non-**async**
- Within a class the same method can appear in more than one chord

Chords: semantics

- A chord is only executed once all the methods in its signature have been called:
    - Calls are buffered until there is a matching chord
        - the implicit buffer supports complex synchronization patterns with little code (see Producer/Consumer later)
    - If multiple matches are possible, nondeterminism applies
    - Execution returns a value to the only non-asynchronous method in the chord (if any)

Chords semantics: example

```
public class Buffer() {
        public String get() & public async put(String i) {
                return i;
        }
}
...
Buffer b = new Buffer();
b.put(“A”)
Console.WriteLine(b.get());      // prints “A”
b.put(“A”); b.put(“B”);
Console.WriteLine(b.get() + b.get()); // prints “AB” or “BA”
b.get(); // blocks until some other thread calls put
```

Polyphonic C#: Discussion

- Combination of two ideas: asynchronous methods and chords
- Asynchronous methods also appear in earlier languages such as Cilk
- Chords: novel idea for message passing communication among more than two threads
- Cω project seems to be discontinued

The Actor model: Erlang

The Actor model

- A mathematical model of concurrent computation, introduced by (Hewitt, 1973) and refined by (Agha, 1985) and others
- Actor metaphor: "active agent which plays a role on cue according to a script"
- Process communication through asynchronous message passing
- No shared state between actors

Actor

- An *actor* is an entity which in response to a message it receives can
  - send finitely many messages to other actors
  - determine new behavior for messages it receives in the future
  - create a finite set of new actors
- Communication via asynchronous message passing
- Recipients of messages are identified by addresses, hence an actor can only communicate with actors whose addresses it has
- A *message* consists of
  - the target to whom the communication is addressed
  - the content of the message

Erlang

- *Erlang*: functional language, developed by Ericsson since 1986
- Erlang implements the *Actor* model

Erlang syntax for concurrency

- When processes (≈ actors) are created using `spawn`, they are given unique process identifiers (or PIDs)

```
PID = spawn(Module, Function, Arguments)
```

- Messages are sent by passing tuples to a PID with the `!` syntax.

```
PID ! {message}.
```

- Messages are retrieved from the mailbox using the `receive()` function with pattern matching

```
receive
        Message1 -> Actions1 ;
        Message2 -> Actions2 ;

        ...
end
```

Example: A simple counter

Interface

```
start() ->
    spawn(counter, counter_loop, [0]).

increment(Counter) ->
    Counter ! inc.

value(Counter) ->
    Counter ! {self(),value},
    receive
        {Counter,Value} -> Value
    end.
```

Counter

```
counter_loop(Val) ->
    receive
        inc ->
            counter_loop(Val + 1);
        {From,value} ->
            From ! {self(),Val},
            counter_loop(Val);
        Other ->
            counter_loop(Val)
end.
```

Actors: Discussion

- Influential model for asynchronous message passing
- Also implemented in various other languages, e.g. Scala and Axum (Microsoft)
- Success story: Ericsson AXD301 switch for telecommunication systems with very high reliability – more than one million lines of Erlang

Message Passing Interface (MPI)

Message Passing Interface (MPI)

- *Message Passing Interface (MPI)*: API specification for process communication via messages, developed in 1993-94
- For parallel programs on distributed memory systems

“Hello, World!“ in MPI

- Processes involved in an MPI execution are identified by *ranks*, i.e. integer numbers 0, 1, ..., numproc – 1
- In the following program, Process 0 gets and prints messages from all other processes

```
MPI_Init(&argc,&argv); // Initialize MPI
MPI_Comm_rank(MPI_COMM_WORLD, &my_rank); // My identifier
MPI_Comm_size(MPI_COMM_WORLD, &numproc);  // Total number of processes
if (my_rank != 0) {
   sprintf(message, "Greetings from process %d!”, my_rank);
   dest = 0;
   MPI_Send(message, strlen(message)+1, MPI_CHAR, dest, tag, MPI_COMM_WORLD);
   } else {
      for (source = 1; source < numproc; source++) {
         MPI_Recv(message, sizeof(message), MPI_CHAR,
           source, tag, MPI_COMM_WORLD, &status);
         printf("%s\n", message);
   }
}
MPI_Finalize();  // Shut down MPI
```

SPMD in MPI

- As seen in the previous program, the most common paradigm used in MPI is SPMD
- Within each process, we take branches based on its rank
- At startup, processes are mapped to processors by the MPI runtime

MPI: Discussion

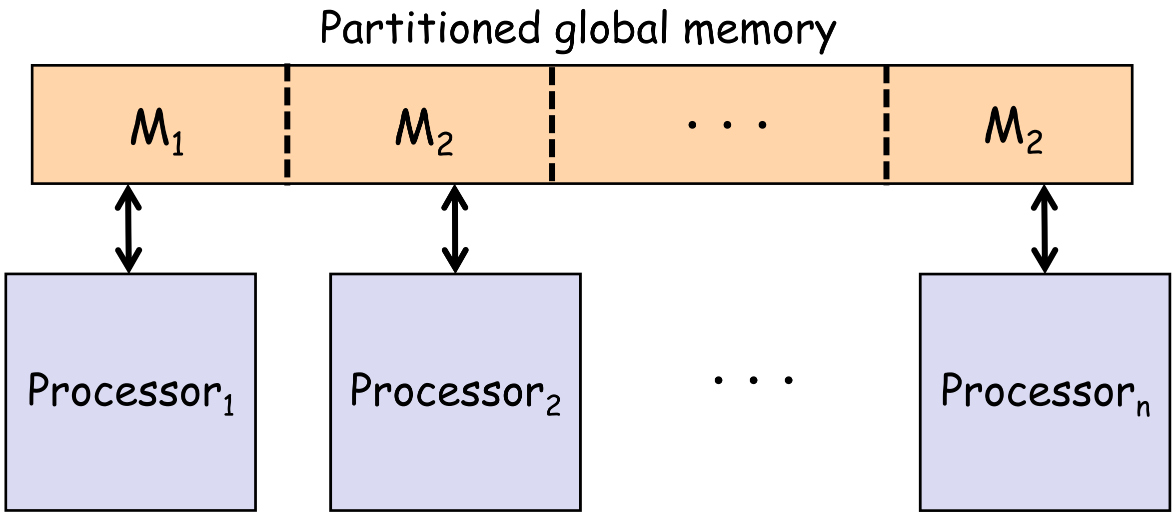
- Dominant model used in high-performance computing
- Good portability: implemented for many distributed memory architectures
- Available as library in many languages, in particular Fortran, C, C++

Shared Memory Approaches

X10

Partitioned global address space (PGAS) model

- Each processor has its own local memory, but the address space is unified
- This allows processes on other processors to access remote data via simple assignment or dereference operations



X10

- Object-oriented language based on the PGAS model, appeared in 2004, developed by IBM
- New threads can be spawned asynchronously: Asynchronous PGAS model
- A memory partition and the threads operating on it are called a *place*

X10 operations (1)

- **async** S
  - Asynchronously spawns a new child thread executing S and returns immediately
- **finish** S
  - Executes S and waits until all asynchronously spawned child threads have terminated

```
def fib(n: int): int {
  if (n < 2) return 1;
  val n1: int;
  val n2: int;
  finish {
    async n1 = fib(n - 1);
    n2 = fib(n - 2);
  }
  return n1 + n2;
}
```

X10 operations (2)

- **atomic** S
    - Executes S atomically
    - S must be nonblocking, sequential, and only access local data

```
...
val node = new Node(data);
atomic {
    node.next = head;
    head = node;
}
...
```

X10 operations (3)

- **when** (E) S
  - Conditional critical region: suspends the thread until E is true, then executes S atomically
  - E must be nonblocking, sequential, only access local data, and be side-effect free

```
...
when (!buffer.full) {
   buffer.insert(item);
}
...
```

X10 operations (4)

- **at** (p) S
    - Executes S at place p
    - Blocks current thread until completion of S

```
class C {
   var x: int;
   def this(n: int) { x = n; }
}

def increment(c: GlobalRef[C]) {
   at (c.home) c().x++;
}
```

X10: Discussion

- Developed as part of the High Productivity Computing Systems initiative of the US Department of Defense: novel languages for supercomputing
- Very similar (in the same project):
  - Chapel, developed by Cray
  - Fortress (Fortran-based)
- More traditional PGAS languages:
  - UPC (Unified Parallel C)
  - Co-array Fortran
  - Titanium (Java extension)

OpenMP

(Some slides adapted from Intel teaching material)

OpenMP

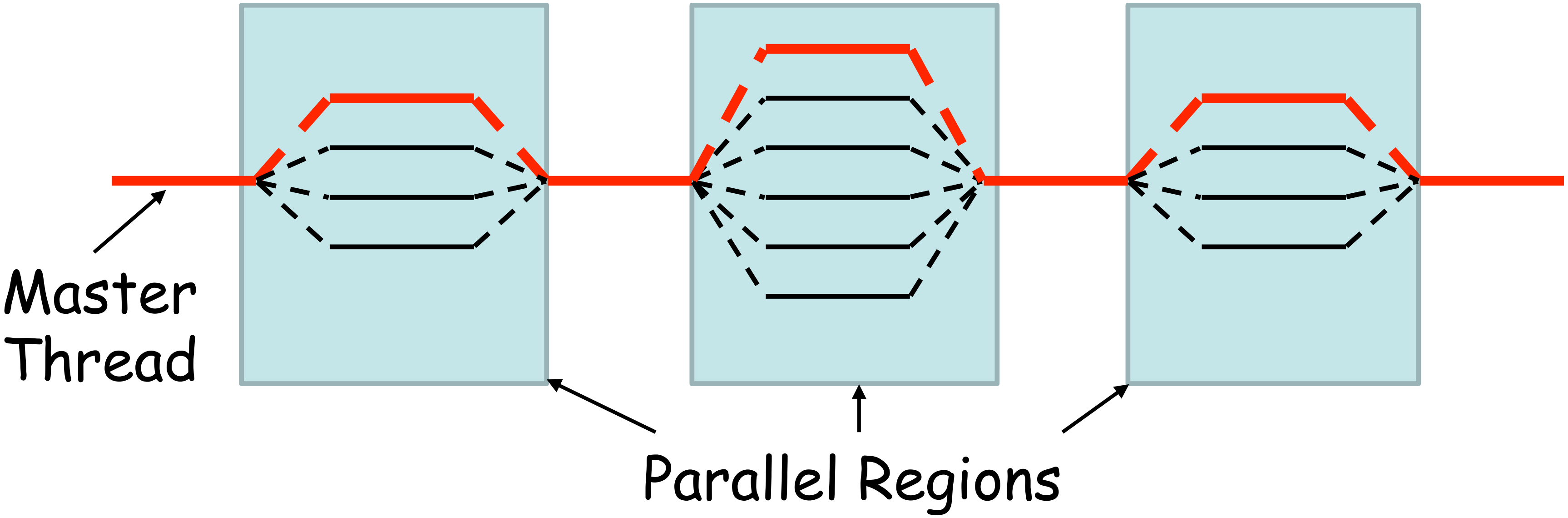
- *OpenMP* (Open Multi-Processing) API for shared memory multithreaded programming, appeared in 1997

- Using preprocessor directives (pragmas) to mark parallel code, may be ignored by other compilers

```
#pragma omp construct [clause [clause]…]
```

Programming model

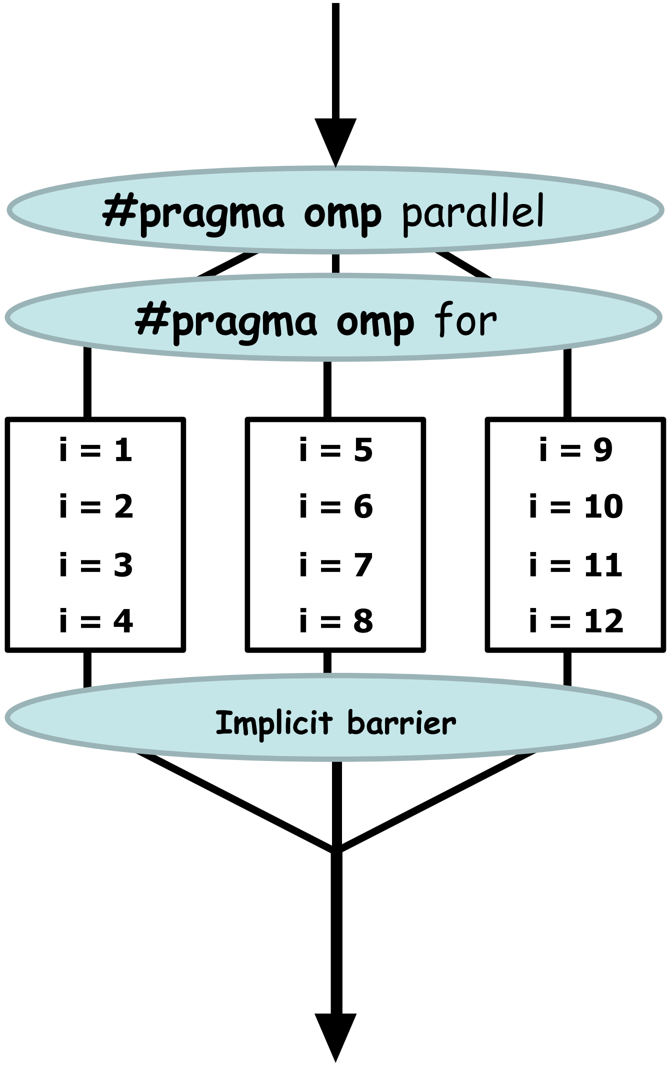
- Fork-join parallelism:
  - Master thread spawns a team of threads as needed
  - Parallelism is added incrementally: that is, the sequential program evolves into a parallel program



Work sharing: data parallelism

- parallel construct forks additional threads
- for and do constructs distribute loop iterations within the threads that encounter the construct

```
// assume N = 100000
#pragma omp parallel
{
   #pragma omp for
   {
       for(i = 0, i < N, i++)
          c[i] = a[i] + b[i];
   }
}
```

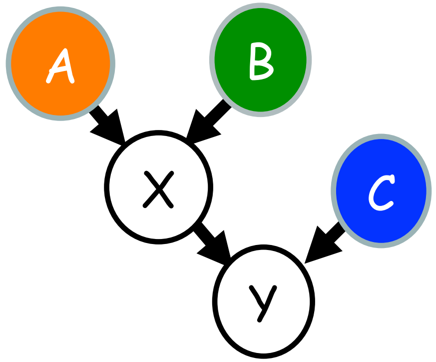


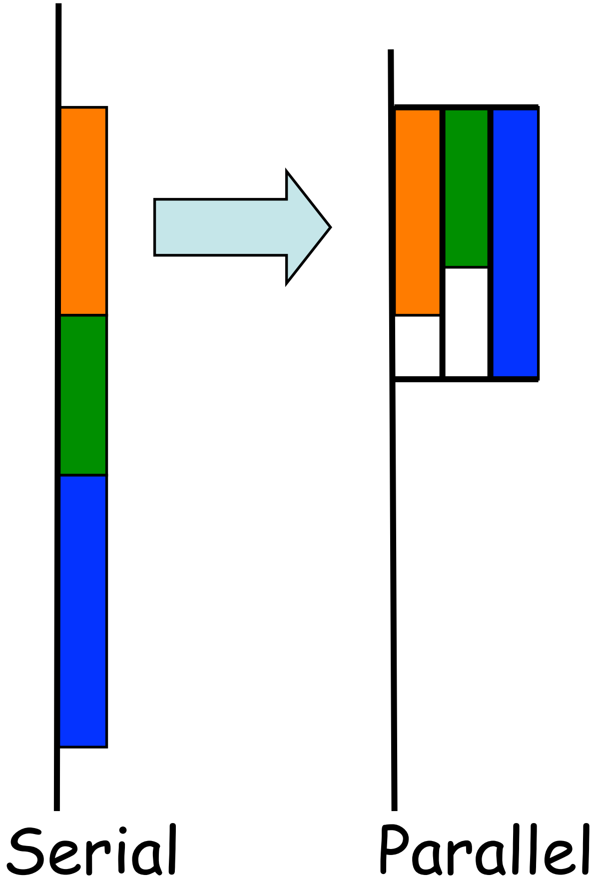
Work sharing: task parallelism

- The sections construct can be used to compute tasks in parallel

```
#pragma omp parallel sections
{
#pragma omp section  /* Optional */
   a = taskA();
#pragma omp section
   b = taskB();
#pragma omp section
   c = taskC();
}

x = combine(a, b);
y = combine(x, c);
```





OpenMP clauses

- OpenMP constructs can be further refined by clauses
- private: make variables local to each thread (shared by default)
- critical section: the enclosed block is executed by at most one thread at a time
- schedule(type, chunk): define the type of scheduling used for work sharing
    - type static: divide work equally between threads (each gets *chunk* iterations)
    - type dynamic: threads may request more iterations when finished (for load balancing)
    - type guided: chunk size decreases exponentially, but won't be smaller than *chunk*

OpenMP: Discussion

- Library approach, no language integration
- Implemented for C, C++, Fortran, available on many platforms
- Supports incremental development of parallel programs, starting with a sequential one
- Some support for load balancing

Coordination Languages: Linda

Linda

- Coordination languages are based on the assumption that a concurrent programming language has two parts:
    - A *computation language*, in which single-threaded execution is defined
    - A *coordination language*, for creation of computations and process communication
- The coordination features are based on the idea of a *tuple space*, which holds data tuples that can be stored and retrieved by the processes
- Linda is the original coordination language, appeared around 1985

Tuple spaces

- A *tuple space* is a collection of tuples such as
  {("test", 11, true), ("test", 3, false), ("b", 23), ... }
- Tuple spaces can be read and modified via the following operations:

out($a_1, \ldots, a_n$)	write tuple
in($a_1, \ldots, a_n$)	read and remove matching tuple
read($a_1, \ldots, a_n$)	read matching tuple
eval(P)	start a new process P

- Pattern matching for **in** and **read**:
  - ($a_1, \ldots, a_n$) can contain both actual and formal parameters
  - If no matching tuple is found, the operation blocks

Example: Tuple spaces

- Assume we have the following tuple space:

  {(“test”, 11, true), (“test”, 3, false), (“b”, 23)}
- Operations:
  - **in**(“a”, x) blocks, no matching tuple
  - **in**(“test”, x, b) removes tuple (“test”, 11, true) and binds 11 to x and true to b (could have also selected tuple (“test”, 3, false))
  - **read**(“test”, x, b) reads tuple (“test”, 3, false)
  - **out**(“a”, 14) puts (“a”, 14) into the tuple space
  - The last action unblocks **in**(“a”, x), which will remove the inserted tuple

Simulating semaphores in Linda

- Semaphores can be implemented in Linda
    - Initilization: tuple space with k tuples (“token”)
    - Implement *down* with **in**(“token”)
    - Implement *up* with **out**(“token”)
- Solution to the mutual exclusion problem:

```
while true do
    in(“token”)
    critical section
    out(“token”)
    non-critical section
end
```

Linda: Discussion

- Communicating processes in Linda are only *loosely coupled*, processes need not know about other processes
- The coordination language is completely orthogonal to computation
    - Distribution of processes is easy
    - Potentially processes written in different languages can cooperate
- Implementations of Linda can be found in several languages such as Java (JavaSpaces) and C