Lecture 9: Languages for Concurrency & Parallelism
Today's lecture

In this lecture you will learn about:

• How to classify various approaches to concurrency in programming languages
• A number of message passing approaches to concurrency: Ada, Erlang (Actor model), Message passing interface (MPI), ...
• A number of shared memory approaches to concurrency: OpenMP, Linda (Coordination languages), Cilk, ...
Classification
Concurrent and parallel languages

Developers today have the choice among a multitude of different approaches to concurrent and parallel programming.
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

![Diagram of asynchronous communication]

- Process P1
  - send
  - message
- Process P2
  - receive
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**

```ada
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

```plaintext
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.

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

```plaintext
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

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

- `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

```haskell
select
  when count < n =>
    accept append(x : in integer) do
      ...
    end append;
  or
  when ...
```
Example: Producer-Consumer problem in Ada

```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 $B$:

  \[
  \text{region } x \text{ when } B \text{ do } S
  \]

  • 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
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)

  \[
  \text{PID} = \text{spawn(Module, Function, Arguments)}
  \]

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

  \[
  \text{PID} ! \{\text{message}\}.
  \]

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

  \[
  \text{receive}
  \]

  \[
  \text{Message1 -> Actions1 ;}
  \]

  \[
  \text{Message2 -> Actions2 ;}
  \]

  \[
  \ldots
  \]

  \[
  \text{end}
  \]
Example: A simple counter

**Interface**

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

increment(Counter) ->
    Counter ! inc.

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

**Counter**

```erlang
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

```c
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++
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

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

• Asynchronous methods do not return any value
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

```java
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

```java
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”
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 is discontinued
Shared Memory Approaches
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

```plaintext
#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

```c
// 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

```c
#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
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
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**($a_1, ..., a_n$)  write tuple
- **in**($a_1, ..., a_n$)  read and remove matching tuple
- **read**($a_1, ..., a_n$)  read matching tuple
- **eval**($P$)  start a new process $P$

Pattern matching for **in** and **read**:

- ($a_1, ..., a_n$) 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:
  • \textbf{in("a", x)} blocks, no matching tuple
  • \textbf{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))
  • \textbf{read("test", x, b)} reads tuple ("test", 3, false)
  • \textbf{out("a", 14)} puts ("a", 14) into the tuple space
  • The last action unblocks \textbf{in("a", x)}, which will remove the inserted tuple
Simulating semaphores in Linda

- Semaphores can be implemented in Linda
  - Initialization: tuple space with \( k \) tuples ("token")
  - Implement \textit{down} with \texttt{in("token")}
  - Implement \textit{up} with \texttt{out("token")}
- Solution to the mutual exclusion problem:

\[
\textbf{while} \ \textbf{true} \ \textbf{do} \\
\quad \texttt{in("token")} \\
\quad \text{critical section} \\
\quad \texttt{out("token")} \\
\quad \text{non-critical section} \\
\textbf{end}
\]
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
Cilk
Cilk

- **Cilk** is a language extension to C/C++, appeared in 1994
- For shared-memory multiprocessing
Cilk keywords

- Cilk extends C/C++ with only few keywords:
  - `cilk`: the routine may be spawned off in parallel
  - `spawn`: the routine may execute in parallel with the parent caller
  - `sync`: wait until all child threads have returned

```cilk
int fib (int n)
{
    if (n < 2) return n;
    else
    {
        int x, y;
        x = spawn fib (n-1);
        y = fib (n-2);
        sync;
        return (x+y);
    }
}
```
Work stealing

- Each processor maintains a queue of threads that are ready to execute
- If the queue of a processor is empty, the processor may steal threads from a random processor’s queue
Cilk: Discussion

• Programmer indicates what can be executed in parallel
• The runtime environment decides how the work is divided among processors
• Hence it is automatic to map Cilk programs to new architectures
• When removing all Cilk keywords from a Cilk program, the result is a valid serial C program
• Cilk is commercially implemented and distributed by Intel
Chair of Software Engineering

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

```python
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)

- **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

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