Concepts of Concurrent Computation

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Lecture 13: Concurrent Languages

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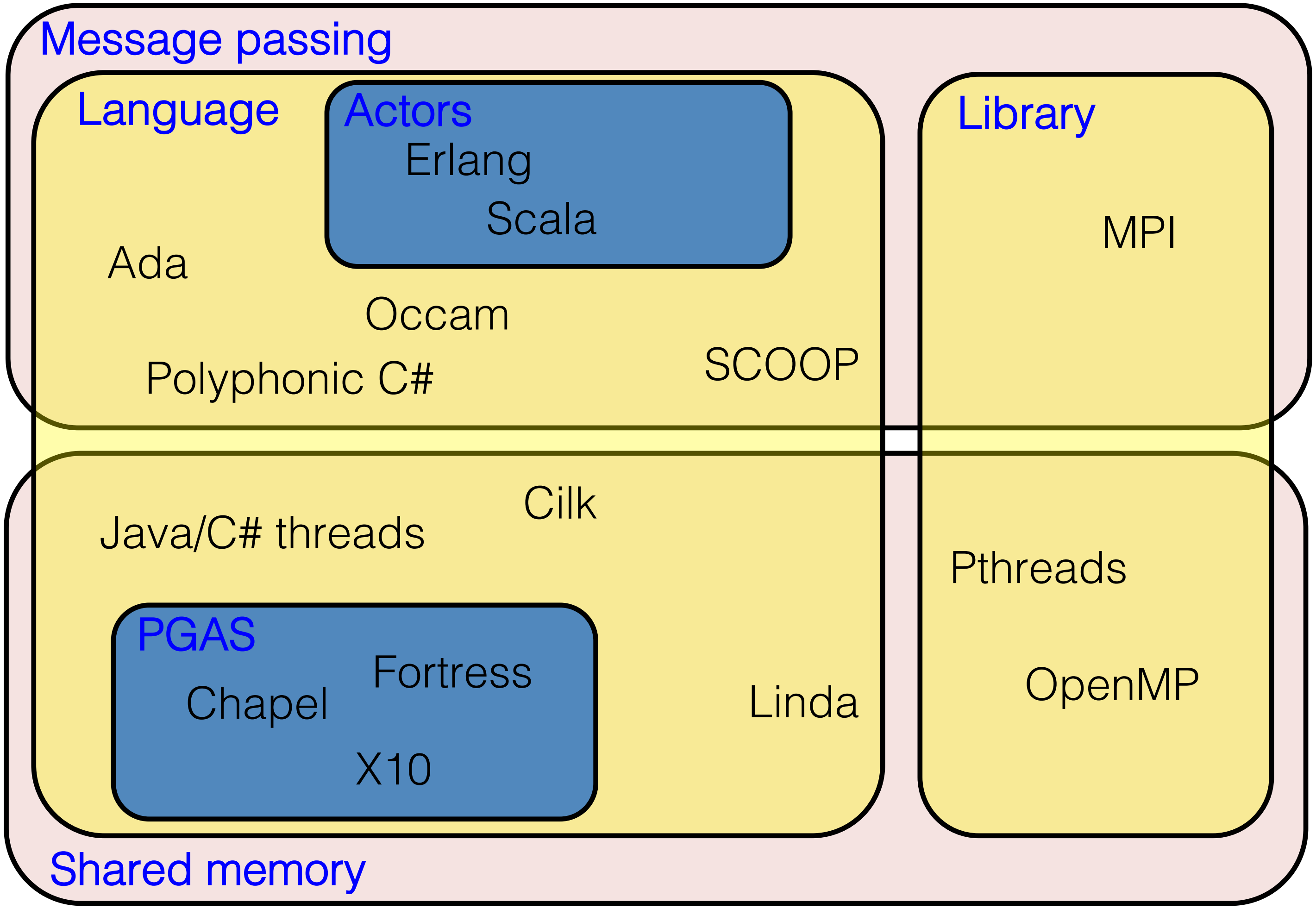
Classification

Concurrent and parallel languages

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



Message passing

Language

Actors

Erlang

Scala

Ada

Occam

Polyphonic C#

SCOOP

Library

MPI

Cilk

Java/C# threads

PGAS

Chapel

Fortress

X10

Linda

Pthreads

OpenMP

Shared memory

Message-passing approaches

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`** is permitted

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

Example: Bounded Buffer

```
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; otherwise it is queued
  - 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
- 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 (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
- 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++

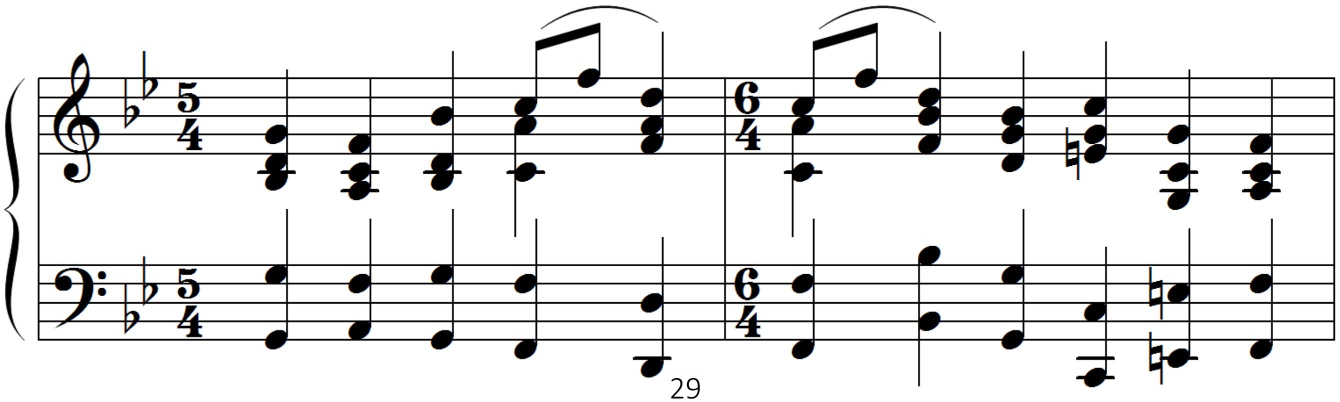
Polyphonic C#

(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 the 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 Producers/Consumers 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”

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

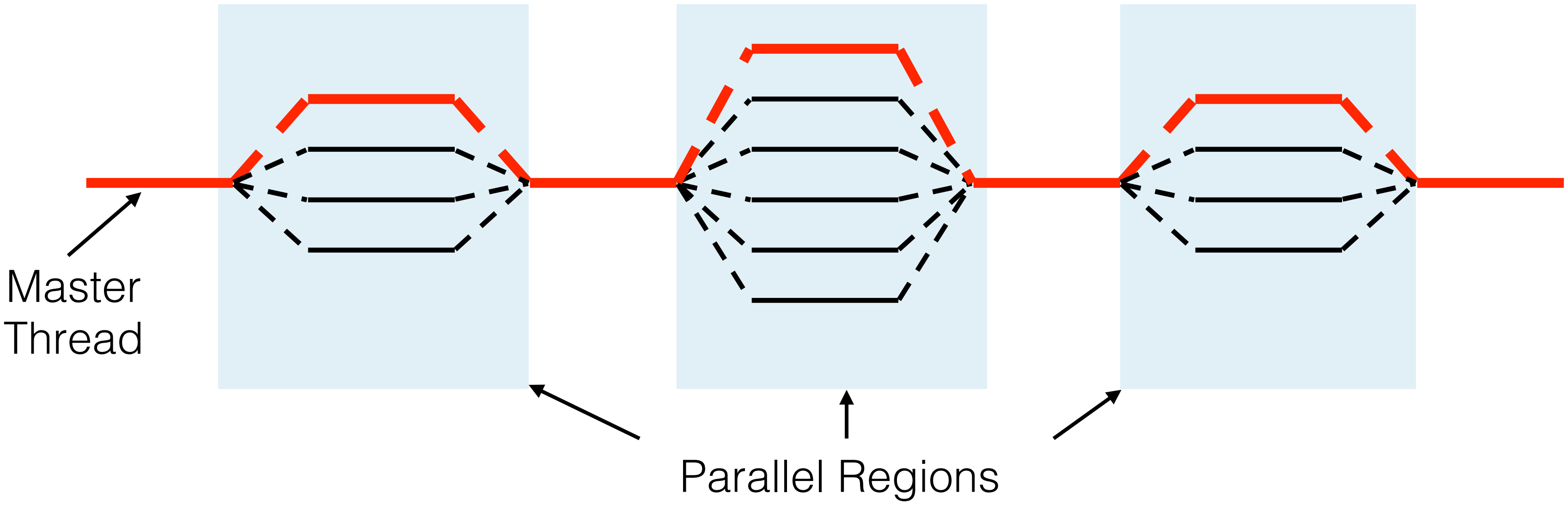
- OpenMP (Open Multi-Processing) API for shared memory multithreaded programming, appeared in 1997

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

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

Programming model

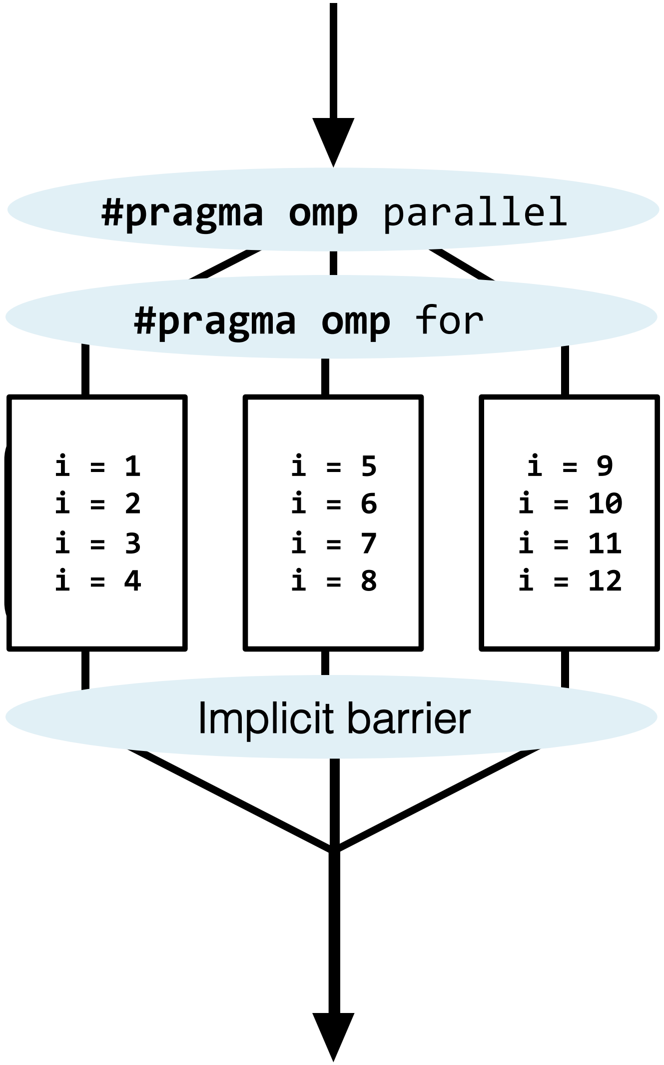
- Fork-join parallelism
  - Master thread spawns a team of threads as needed
  - Parallelism is added incrementally: that is, the sequential program evolves into a parallel program



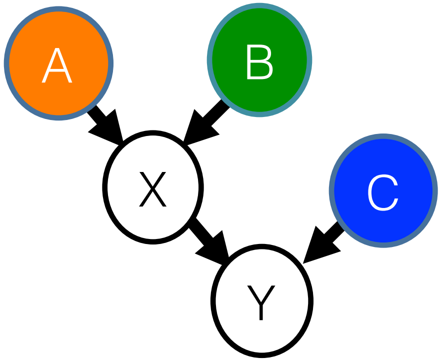
Work sharing: data parallelism

- **`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];
   }
}
```



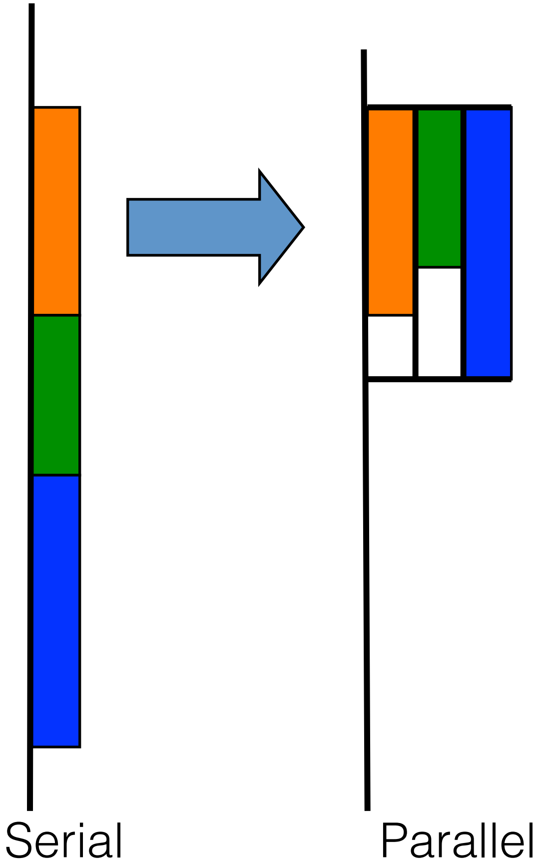
Work sharing: task parallelism



- 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$(a_1, ..., a_n)$	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
  - `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

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

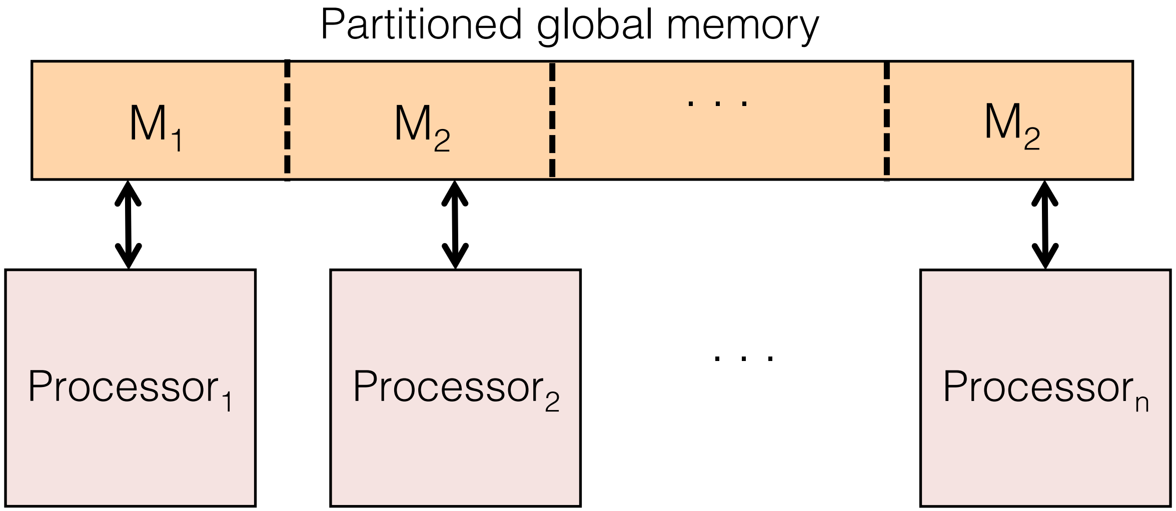
Cilk: Discussion

- 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

X10

Partitioned global address spaces (PGAS)

- 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)

- `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 (3)

- `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)

Conclusion

- Developers have a wide choice of languages for concurrency and parallelism
    - Important to know which languages target which applications
- Many are based on very innovative language concepts
    - Adoption can be low because of the learning curve
- No dominant innovative language for concurrency yet
    - Interesting field for research