CHALMERS

UNIVERSITY OF GOTHENBURG

Models and languages of concurrent computation

Lecture 12 of TDA384/DIT391 Principles of Concurrent Programming

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Based on course slides by Carlo A. Furia and Sandro Stucki

Today's menu

- Classifying approaches to concurrency
- Message passing models and languages
  - Ada
  - Go
  - SCOOP
  - MPI
- Shared memory models and languages
  - Linda
  - OpenMP
  - Cilk
  - X10
- Other languages for concurrency

Credits

Part of today's presentation is based on material developed by S. Nanz for the Concepts of Concurrent Computation course given at ETH Zurich in 2015.

Classifying approaches to concurrency

Concurrency approaches galore

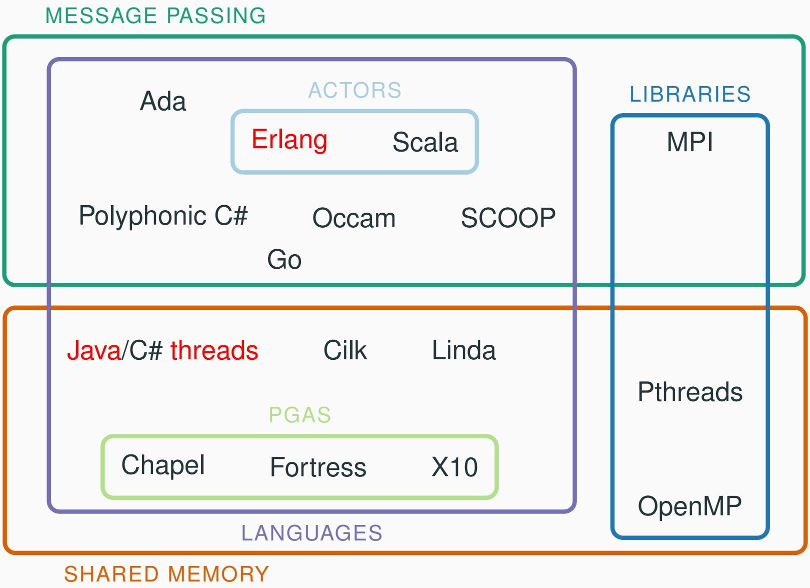
This course mainly focused on two representative approaches to concurrent programming:

- shared-memory concurrency with Java threads
- message-passing concurrency with Erlang processes

There are many other variants of concurrency models and languages. This class gives an overview of a few approaches that are historically and practically significant.

We try to classify languages according to the features of their concurrency models. The categories are necessarily fuzzy, because actual languages often combine different models, but they are useful to navigate the rich landscape of concurrent and parallel programming.

Concurrency languages galore



Message passing: synchronous vs. asynchronous

A natural classification of message passing primitives is between synchronous and asynchronous:

- synchronous: sender and receiver of a message block at the same time until they have exchanged the message
  Examples: phone calls, live TV, Ada (rendezvous)
- asynchronous: sender and receiver of a message need not block – sending and receiving can occur at different times
  Examples: email, movies, Erlang (messages)

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Erlang uses asynchronous message passing with mailboxes:

- sending is non-blocking
- receiving is blocking (when no suitable message is available in the recipient's mailbox)

Shared memory: synchronous vs. asynchronous

For shared-memory models, the distinction between synchronous and asynchronous is less sharp, and mainly applies to synchronization primitives:

- synchronous primitives require all synchronizing parties to convene at a common time
  Examples: traditional lectures, barrier synchronization
- asynchronous primitives share information between synchronizing parties without requiring them to access the information at the same time
  Examples: take-home lab assignments, message boards, Linda

Addressing

Communication requires addresses: identifiers to match senders and receivers. A natural classification of communication primitives is according to their usage of addresses:

- symmetric: the sender specifies the receiver, and the receiver specifies the sender
  Examples: email with filtering, communication with channels
- asymmetric: either the sender specifies the receiver, or the receiver specifies the sender – but not both
  Examples: regular mail, phone calls (without caller identification), Erlang, sockets
- indirect: sender and receiver do not refer to each other directly, but communicate through an intermediary
  Examples: communication with channels, Go, Linda

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  Examples: communication with channels, Go, Linda

Erlang uses asymmetric message passing: sending `To ! Message` specifies the recipient `To`; receiving `receive Msg -> Msg end` need not specify the sender but only the message content.

Message passing models and languages

Message passing models and languages

Ada

Ada

Ada is an object-oriented programming language first developed in 1977 by the US Department of Defense to have one unified language for all software development. It still is under active development.

Ada's design goals include:

- suitable to build highly reliable systems
- reusable, modular components
- concurrency supported at language level

It introduced several features to programming language practice:

- strong typing and safe pointers
- modularity mechanisms (packages)
- exceptions
- high-level concurrency primitives

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Ada is named after Ada Lovelace (1815–1852), often considered the first programmer (before computers!)

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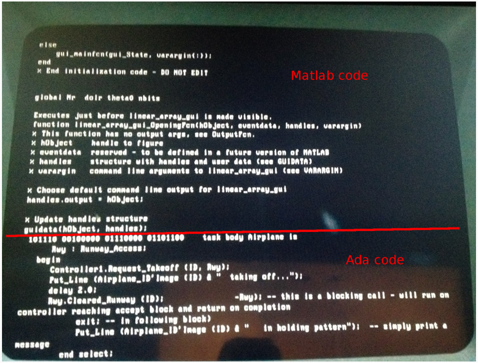
Featured in:



(The Matlab code is an anachronism)

Concurrency in Ada

Ada's support for concurrency includes both synchronous and asynchronous mechanisms:

- Concurrent execution uses tasks, which communicate via synchronous message passing using rendezvous
- Protected objects are a shared-memory model which extends monitors with waiting guards
- The language includes nondeterministic statements

Tasks

Procedures in Ada may include tasks:

- Each task has an interface and an implementation
- When a procedure starts executing, its tasks are implicitly activated

```
procedure Meetings is

  task Point is
    -- task interface
  end;

  task body Point is
    -- task implementation
  end Point;

  -- rest of procedure
end Meetings;
```

Rendezvous points

Task coordinate using synchronous primitives called rendezvous:

- Task interfaces declare entry points: actions they synchronize on
- Task implementations use `accept` statements to indicate where rendezvous take place

```
task Point is
  entry Meet;
end;
```

```
task body Point is
begin
  -- before meeting
  accept Meet do
    -- during meeting
  end Meet;
  -- after meeting
end Point;
```

Synchronization using rendezvous

Rendezvous are a synchronous mechanism, where clients synchronize with tasks by invoking an entry point:

- the client blocks waiting for the task to reach the corresponding entry point; and resumes after the task has executed the rendezvous' body
- a task at an **accept** statement matches a client that is invoking the corresponding entry point

```
task body Point is
begin
  -- before meeting
  accept Meet do
    -- during meeting
  end Meet;
  -- after meeting
end Point;
```

```
-- client
declare
  P: Point;
begin
  -- wait until P reaches Meet
  P.Meet;
  -- continue after P executes accept
end;
```

Rendezvous with parameters

Entry points can include parameters, whose actual values are exchanged during rendezvous:

```
task Buffer is
  entry Put (Item: in Integer);
  entry Get (Item: out Integer);
end;
```

```
-- client synchronizing
B.Put(42);
```

Nondeterminism

Nondeterministic **select** statements group multiple guarded **accept** statements. During a rendezvous, one of the **accept** statements whose guard evaluates to true gets nondeterministically executed.

```
task body Buffer is
  begin loop select
      when Count < SIZE => -- buffer not full
        accept Put (Item: in Integer) do
          -- add Item to buffer
        end;
     or -- when neither full nor empty: nondeterministic choice
      when Count > 0 => -- buffer not empty
        accept Get (Item: out Integer) do
          -- remove item from buffer
        end;
    end select; end loop;
end Buffer;
```

Protected objects

Protected objects provide high-level shared-memory concurrency with features similar to monitors:

- all attributes are private
- procedures, functions, and entries may be public

In a protected object:

- Functions do not modify object state, therefore functions calls may execute concurrently on the same protected object
- Procedures and entries may modify object state, therefore they execute with exclusive access to protected objects
- Entries may include guards, which provide a synchronization mechanism similar to conditional critical regions

Conditional critical regions

A conditional critical region is a critical region with a guard `B`.
In Java pseudo-code:

```
synchronized (object) when (B) {
  // critical region guarded by B
}
```

Threads queue to enter a conditional critical region:

- when the lock protecting the region becomes available, the first thread *P* in the queue tries to acquire it
- if *P*'s guard `B` to the region evaluates to true, *P* holds the lock and enters the critical region
- if *P*'s guard `B` to the region evaluates to false, *P* releases the lock immediately and goes back into the queue

Guarded entries – implementing semaphores in Ada

Ada's protected objects provide conditional critical regions using guards on entries.

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

protected body Semaphore is
  procedure Up is
  begin
    Count := Count + 1;
  end Up;

-- conditional critical region
entry Down when Count > 0 is
  begin
    Count := Count - 1;
  end Down;

function Get_count
         return Natural is
  begin
    return Count;
  end Count;
end Semaphore;
```

Message passing models and languages

Go

Go

Go (also called golang) is a procedural programming language first developed at Google in 2009. It is available as open source.

Go's main features include:

- static typing with type inference
- a packaging system that integrates with the build system
- memory safety checks performed by the compiler
- concurrency supported at language level with goroutines and channels

Go's creators include Ken Thompson and Rob Pike, who were also main developers of C and Unix in the 1970s.

Concurrency in Go

Go's support for concurrency includes:

- Goroutines: lightweight processes, similar to Erlang's processes but supporting both shared memory and message-passing communication
- Channels: a buffered mechanism to exchange messages between goroutines

Goroutines

A goroutine is a lightweight process executing an arbitrary function.

Using the keyword **go** in front of a regular function call spawns a goroutines executing that call:

```
func hello(who string) {
  fmt.Println("Hello %s!", who)
}

// spawn two instances of hello,
// printing "Hello world!" and "Hello class!" in any order:
go hello("world")
go hello("class")
```

Keyword **go** produces a behavior similar to as Erlang's `spawn`.

The name goroutine is a play on the name coroutine, a generalization of subroutines for concurrency (goroutines can implement coroutines).

Channels

Goroutines can exchange messages through channels.

Each channel:

- is declared using the modifier `channel`
- has a type, denoting the type of its messages
- is accessible to goroutines that have a reference to it
- has a finite capacity – zero by default

```
  // a channel ‘stringMsg’ with capacity 0 (default)
  // to exchange messages consisting of strings
var stringMsg chan string = make(chan string)

  // a channel ‘ints’ with capacity 30
  // to exchange messages consisting of integers
var ints chan int = make(chan int, 30)
```

Message passing through channels

Addressing is indirect in Go: messages are exchanged through channels, and hence senders and receivers communicate indirectly, without being explicitly aware of each other.

Sending and receiving are primitives of the language using the `<-` operator:

SENDING	RECEIVING
`ch <- v`	`m := <- ch`
send the value of expression `v` to channel `ch`	receive a message from channel `ch` and store it in variable `m`

Message passing: synchronous vs. asynchronous

Synchronization using message passing behaves differently according to the capacity of channels:

Channels with capacity zero (unbuffered) are synchronous: a receiver evaluating `<- ubch` blocks until a value is available in unbuffered channel `ubch`; and a sender evaluating `ubch <- v` blocks until a receiver is available to receive message `v` on `ubch`.

Channels with positive capacity (buffered) are potentially asynchronous: a receiver evaluating `<- bch` does not block unless buffered channel `bch` is empty; and a sender evaluating `bch <- v` does not block unless `bch` is full.

Channels store and deliver messages in FIFO (first-in first-out) order; messages sent to a channel are enqueued in order, and are received starting from the one that has been in the channel the longest.

Message passing: synchronous vs. asynchronous

Synchronization using message passing behaves differently according to the capacity of channels:

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Channels with positive capacity (buffered) are potentially asynchronous: a receiver evaluating `<- bch` does not block unless buffered channel `bch` is empty; and a sender evaluating `bch <- v` does not block unless `bch` is full.

Message passing with unbuffered channels is similar to Ada's rendezvous; message passing with buffered channels is similar to Erlang's send/receive but with finite capacity.

Producer-consumer with bounded buffer in Go

The features of Go buffered channels make it very easy to implement a producer-consumer with bounded buffer:

```
const Size = 10                      // capacity of buffer
var buffer = make(chan int, Size) // channel with capacity ‘Size’

func put(item int) {
  buffer <- item    // send item to buffer
}                   // block if full

func get() (item int) {
  return <- buffer  // receive item from buffer
}                   // block if empty
```

Nondeterminism

The `select` statement support nondeterministic message reception from multiple channels. In the following example:

- receive the first message that is available on channels `greetingsCh` and `goodbyeCh`
- block if no messages are available on either channel
- receive from one nondeterministically chosen channel if messages are available on both channels
- time out after 3 seconds of wait

```go
select {
  case m := <- greetingsCh:
    fmt.Println("Greetings from %s", m)
  case m := <- goodbyeCh:
    fmt.Println("Goodbye from %s", m)
  case <- time.After(3 * time.Second)
    fmt.Println("No messages for 3 seconds")
}
```

Nondeterminism

The `select` statement support nondeterministic message reception from multiple channels.

Blocking and waiting can be avoided completely by adding a `default` case, which executes immediately if none of the channels are ready:

```go
select {
  case m := <- greetingsCh:
    fmt.Println("Greetings from %s", m)
  case m := <- goodbyeCh:
    fmt.Println("Goodbye from %s", m)
  default:
    fmt.Println("I'm not waiting for messages!")
}
```

Message passing models and languages

SCOOP

SCOOP

SCOOP (Simple Concurrent Object-Oriented Programming) is the part of the Eiffel programming language that deals with concurrency.

Each object is associated at runtime to a single thread (called "processor" in SCOOP jargon), which is the sole responsible for executing calls on the object.

Objects that are associated with different threads are called separate.

The type modifier `separate` indicates that calls to objects of that type may be handled by a different thread.

```
cnt: INTEGER                          -- run by Current object's thread
shared_counter: separate COUNTER  -- may be run by different thread
```

Method calls

Method calls are implicit synchronization events in SCOOP.

The call `o.m` of procedure method `m` on object `o`:

- is synchronous if `o` has type not separate
- may be asynchronous if `o` has type separate

If `m` is a function (returning a value), the call blocks until the result is computed – that is it behaves like a non-separate call.

A call `o.m` is executed by the single thread handling object `o`:

- the client's thread sends a message to `o`'s handler, requesting to execute `m`
- the client request is added to a queue in `o`'s handler
- if `m` is a function, after `o`'s handler gets to execute `m`, it sends the results back to the client

This explains how SCOOP uses message-passing concurrency.

Atomic method calls

Before a method starts executing, it gets exclusive access to all its separate arguments. This makes it easy to ensure that methods execute atomically:

```
-- transfer 'amount' from 'source' to 'target'
transfer (source, target: separate BANK_ACCOUNT; amount: INTEGER)
do -- lock both 'source' and 'target' before proceeding
  source.withdraw(amount)
  target.deposit(amount)
end
```

Assertions: preconditions and postconditions

Eiffel supports assertions such as pre- and postconditions:

preconditions: a call `o.m (a)` to method `m` is valid only if `o` and `a` satisfy `m`'s precondition

postconditions: the implementation of a method `m` is correct only if every valid call `o.m (a)` terminates in a state where `o` satisfies `m`'s postcondition

```
withdraw (amount: NATURAL)
require  -- precondition: cannot withdraw more than ‘balance’
  amount <= balance
do
  balance := balance - amount
ensure   -- postcondition: ‘balance’ is decreased by ‘amount’
  balance = old balance - amount
end
```

Preconditions as waiting conditions

Preconditions that refer to separate arguments double as waiting conditions in SCOOP:

```
class PRODUCER
  put (b: separate BUFFER;
       item: INTEGER)
   -- wait until b not full
   require
     not b.is_full
   do
     b.append (item)
   end
end
```

```
class CONSUMER
  get (b: separate BUFFER)
      : INTEGER
   -- wait until b not empty
   require
     not b.is_empty
   do
     Result := b.remove
   end
end
```

Message passing models and languages

MPI

MPI

MPI (Message Passing Interface) is an API specification for inter-process message-passing, initially developed in the early 1990s.

MPI is the dominant standard in high-performance computing. MPI mainly targets parallel programs on distributed-memory systems – multi-processor systems where each processor has its own memory – although it is routinely used on shared-memory architectures as well.

MPI is portable:

- available as a library for many languages
- high-performance implementations in C/C++ and Fortran
- implementations for many different computer architectures

Process ranks

MPI supports multiple styles of programs; the most common one is SPMD (single program, multiple data): multiple processes execute the same program on different processors and different portions of the input.

Each process has a rank, which is an integer identifier ranging from `0` to `num_procs - 1`, where `num_procs` is the total number of processes. MPI programs assign tasks to different processes according to their rank.

Hello world in MPI for C

Process with rank 0 prints messages received from other processes.

```c
char message[256];  int my_rank, num_procs, other_rank;
MPI_Init(&argc, &argv);                          // initialize MPI
MPI_Comm_rank(MPI_COMM_WORLD, &my_rank);   // get my rank
MPI_Comm_size(MPI_COMM_WORLD, &num_procs); // number of processes
// different behavior according to rank
if (my_rank != 0) { // send message to process 0
   sprintf(message, "Hello from #%d!", my_rank);
   MPI_Send(message, sizeof(message), MPI_CHAR, 0,
            0, MPI_COMM_WORLD);
} else { // proc 0: receive messages from other processes
  for (other_rank = 1; other_rank < num_procs; other_rank++) {
  { MPI_Recv(message, sizeof(message), MPI_CHAR, other_rank,
             0, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
     printf("%s\n", message); }
}
MPI_Finalize();  // shut down MPI
```

Shared memory models and languages

Shared memory models and languages

Linda

Linda

Linda is a coordination language developed in 1985 by Gelernter and Carriero. Using a coordination language means splitting the features of a concurrent programming language in two parts:

- a computation language, which executes computations sequentially
- a coordination language, which supports creating concurrent processes and synchronizing them

Linda is a set of primitives that define a coordination language based on the notion of tuple space: shared memory is organized in tuples which can be stored and retrieved by processes

Tuple spaces

A tuple space is a shared collection of tuples of any size and type:

$$\left[\langle \texttt{count}, 3\rangle\ \langle \texttt{birthday}, 20, \texttt{January}\rangle\ \langle 1, 1, 2, 3, 5, 8\rangle\right]$$

Multiple copies of the same tuple may exist in a tuple space.

The metaphor of the message board helps us understand the primitives used to access a tuple space:

`out`$(a_1, \ldots, a_n)$	write tuple	post message to board
`in`$(a_1, \ldots, a_n)$	read and remove tuple	remove message from board
`read`$(a_1, \ldots, a_n)$	read tuple	read message from board
`eval`(P)	start new process	—

Operations `in` and `read` pattern match on their arguments, and block until a matching tuple is in the space (similarly to Erlang's **`receive`** but on shared memory); when multiple tuples match, one is chosen nondeterministically.

Implementing semaphores in Linda

A counting semaphore can be implemented by putting as many copies of tuple ⟨`"semaphore"`, *id*⟩ as the semaphore's count, where *id* is a unique identifier of the semaphore instance.

```
public class TupleSemaphore implements Semaphore {
 // initialize with capacity tuples
 TupleSemaphore(int capacity)
 { for (int i = 0; i < capacity; i++) up(); }
 // add a copy of the tuple; do not block
 void up()
 { out("semaphore", hashCode()); }
 // remove a copy of the tuple; block if no tuples are in the space
 void down()
 { in("semaphore", hashCode()); }
}
```

Shared memory models and languages

OpenMP

OpenMP

OpenMP (Open Multi-Processing) is an API specification for shared-memory multi-threaded programming, initially developed in the late 1990s.

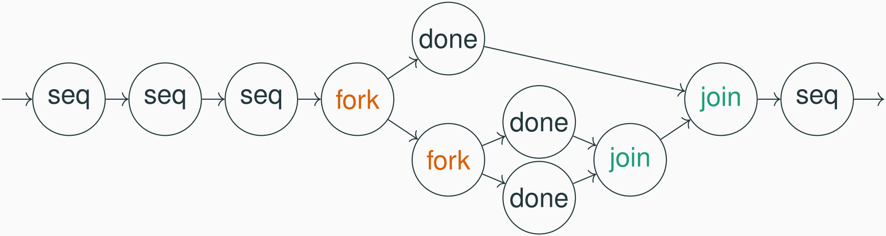
OpenMP mainly targets fork/join parallelism and numerical programming. It includes parallel extensions of loops, which support incrementally adding parallelism to sequential programs. The extensions are available as pre-processor macros, which are ignored by a compiler without OpenMP support.

Implementations of the OpenMP API are available in C/C++ and Fortran.

Fork/join parallelism

OpenMP's programs follow the fork/join model of parallelism:

- a master thread spawns parallel threads when needed, waits for them to terminate, and combines their results
- the overall program alternates sequential and parallel phases

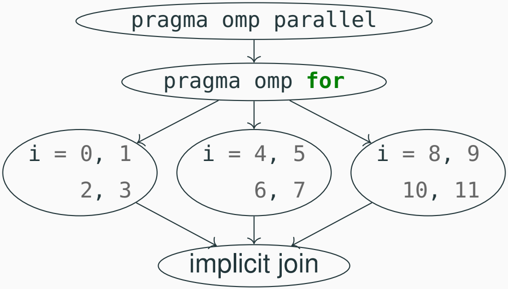


Data parallelism

With data parallelism, parallel threads process disjoint portions of the input data – typically stored in arrays or matrices:

- `parallel` forks new threads
- parallel **for** and **do** loops assign work to the running threads and join their results

```
#pragma omp parallel
{
#pragma omp for
  {
    for (i = 0; i < 12; i++)
      c[i] = a[i] + b[i];
  }
}
```



Task parallelism

With task parallelism, parallel threads compute different functions of the input:

- `parallel sections` forks new threads
- `section` assigns a piece of code to one of the parallel threads

```
#pragma omp parallel sections
{ // compute a, b, c in parallel
#pragma omp section
  a = computeA();
#pragma omp section
  b = computeB();
#pragma omp section
  c = computeC();
} // implicit join
return combine(a, b, c);
```

Clauses

Synchronization between parallel threads can be specified indirectly using clauses:

- `private(x)`: each thread has a private copy of variable `x` (counter loop variables are private by default; other variables are shared by default)
- `critical`: the block is executed by at most one thread at a time
- `schedule(type, chunk)`: set the way work is split and assigned to threads:
  - type `static`: each thread gets `chunk` iterations per round
  - type `dynamic`: threads that finish earlier may get more iterations
  - type `guided`: chunk size decrements exponentially (but won't be smaller than `chunk`)

Shared memory models and languages

Cilk

Cilk

Cilk is a language extension to C/C++ for shared-memory multi-threaded programming, initially developed in the mid 1990s.

Cilk targets fork/join parallelism by extending C/C++ with just few constructs:

- programmers indicate what can be executed in parallel
- the runtime environment allocates work to threads using work stealing
- a Cilk program stripped of all Cilk keywords is a valid sequential C/C++ program

A commercial Cilk implementation is distributed by Intel.

Cilk keywords

Cilk adds only few keywords to C/C++:

- **spawn** `f()`: the call `f()` can be run in parallel
- **sync**: wait until all parallel calls have completed
- **cilk**: declares a function that may use Cilk constructs (not used in recent versions of Cilk)

```
cilk int fibonacci(int n) { // compute n-th fibonacci number
  if (n < 2) return n;
  else {
    int x, y;
    x = spawn fibonacci(n - 1); // can fork
    y = spawn fibonacci(n - 2); // can fork
    sync;                       // wait for x and y
    return x + y;
  }
}
```

Shared memory models and languages

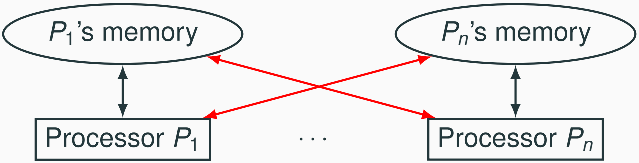
X10

PGAS

PGAS (Partitioned Global Address Space) is a shared-memory computer architecture:

- each processor has its local memory
- all local memories share a global address space

Thus, every processor can read and write any other processor's memory in the same way it accesses its local memory.



X10

X10 is an object-oriented language for multi-threaded programming on PGAS, developed in 2004 by IBM.

X10 supports asynchronously creating threads that work on places – a memory partition where a bunch of threads operate.

Fork/join operations

The operations **`async`** and **`finish`** support fork/join parallelism:

- **`async`** `{ B }`: asynchronously spawn a thread executing block `B`
- **`finish`** `{ B }`: execute block `B` and wait until all threads spawned in `B` have terminated

```
class Fibonacci {
  public static def fibonacci(n: Int): Int {
    if (n < 2) return n;
    val x: Int; val y: Int;
    finish {
      async x = fibonacci(n - 1);
      async y = fibonacci(n - 2);
    } // x and y are available
    return x + y;
  }
}
```

Critical regions

Other operations define critical regions:

- **atomic** `{ B }`: execute block `B` atomically; `B` must be nonblocking, sequential, and only access data in local memory
- **when** `(C) { B }`: define `B` as a critical region with blocking condition `C`; `B` and `C` must be nonblocking, sequential, and only access local data (`C` should also be without side effects)

```
class Buffer[T] {
  private var buffer: List[T];
  private var count: Int;

  def put(item: T)
  { atomic {buffer.add(item); count += 1;}}

  def get(): T
  { when (!buffer.isEmpty()) {count -= 1; return buffer.remove();}}
}
```

Code mobility

The construct **at** `(p) { B }` supports executing code at a different location:

- suspend execution in the current place
- transmit code `B` and the data it uses to place `p`
- execute `B` at place `p` and wait for termination
- if `B` is an expression, transmit result back

```
class Counter {
  private var count: Int;
  def this(n: Int)
  { count += n; }
}
```

```
// somewhere else in the code
def increment(cnt: GlobalRef[Counter]) {
  // increment cnt by 1 at its place
  at (cnt.home) cnt(1);
}
```

Other PGAS languages

X10 was developed in a US Department of Defense project about novel languages for supercomputing. Other similar languages were developed in the same project:

- Chapel by Cray
- Fortress by Sun – based on Fortran

Other preexisting PGAS languages follow more standard models of parallelism:

- UPC (Unified Parallel C)
- CAF (Coarray Fortran)
- Titanium – a dialect of Java

Other languages for concurrency

But wait – there's more!

Developing models and languages for concurrent programming that are practical and efficient is still a very active research area.

A few other widely used languages/libraries:

- Pthreads (POSIX threads) are the standard API for shared-memory thread programming in C/C++. They provide features similar to Java/C# threads.
- C# threads are very close to Java's. C# also includes features for fork/join parallelism (`async` and `await` keywords).

But wait – there's more!

Some other niche/experimental approaches:

- Occam is a language using message-passing communication with channels; it follows the theoretical model of the process algebra CSP (Communicating Sequential Processes)
- Polyphonic C# is an extension of C# with asynchronous methods and chords – a feature to combine the results of asynchronous methods
- The developers of C# experimented with several high-level concurrency models, including a form of transactions using LINQ (Language Integrated Query, which introduced functional features in C#). If you are interested in some details: `http://joeduffyblog.com/2016/11/30/15-years-of-concurrency/`.

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