Concurrent and Parallel Programming, Part II

Programming Languages

CS 214

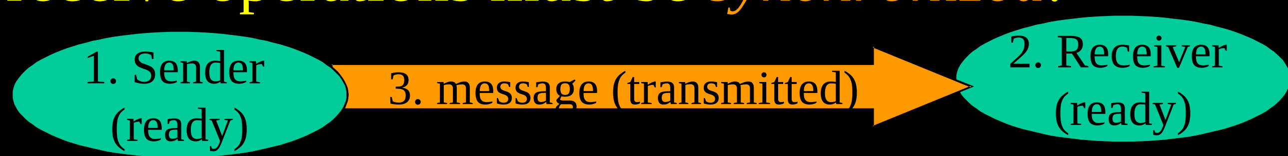
Distributed Synchronization

Semaphores, locks, condition variables, monitors, are *shared-memory* constructs, and so *only useful on a tightly-coupled multiprocessor*.

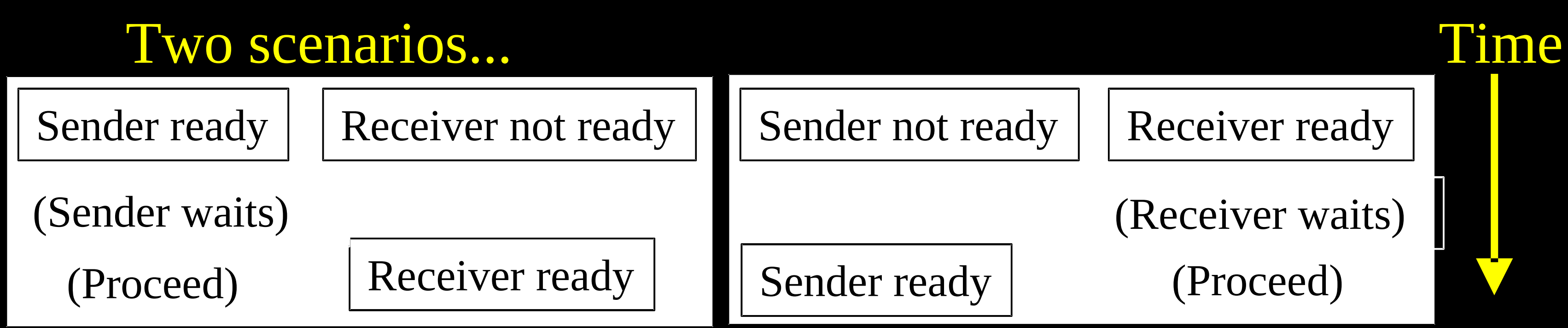
- They are of *no use* on a *distributed multiprocessor*

On a distributed multiprocessor, processes can communicate via *Message-passing – using send() and receive()* primitives.

- If the message-passing system has *no storage*, then the send/receive operations must be *synchronized*:

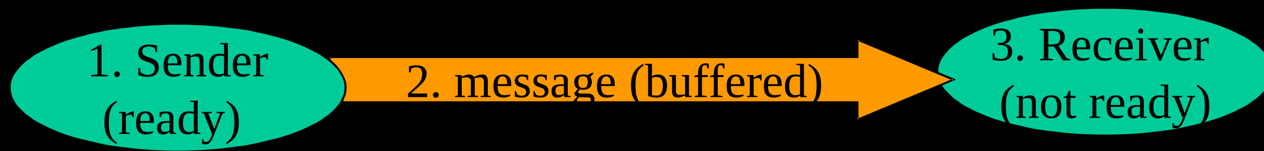


Two scenarios...



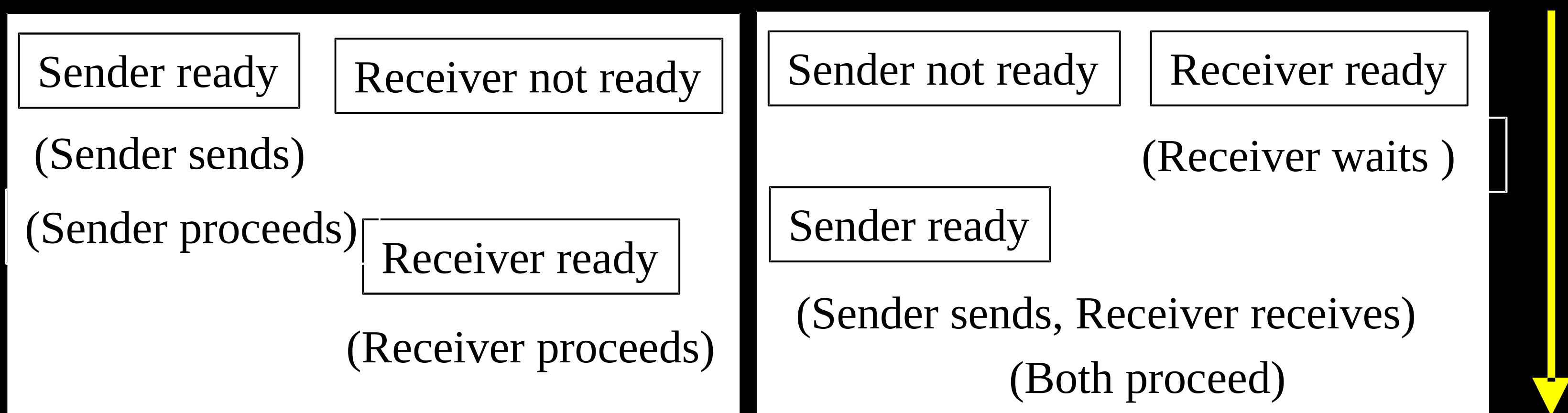
Asynchronous Communication

–If the message-passing system has *storage to buffer the message*, then the send/receive operations can proceed *asynchronously:*



The receiver can then retrieve the message when it is ready…

Two scenarios… Time



Message-buffering eliminates some (but not all) of the waiting.

Message-Passing Languages

Some languages support message-passing between *Actor*:

- *Erlang* is a functional language developed at Ericcson and used by Nortel, T-Mobile, Facebook (chat, WhatsApp), and 20+ others.


```
B!{self(),{digits, [2,3,5]}}
```

```
receive
 {A, {digits, nums}} ->
  analyze(nums);
end
```

- *Scala* is a hybrid OO+functional language used at Netflix, LinkedIn, Twitter, Tumblr, Foursquare, Sony, and other companies:

```
B! digits(2,3,5)
```

```
receive {
  case digits(nums) =>
  analyze(nums);
}
```


An Ada Task

… has 3 characteristics:

- its own thread of control;
- its own execution stat (that it stores); and
- Mutually exclusive subprograms (aka *entry procedures*)

Entry procedures are *self-synchronizing subprograms* that another task can invoke for task-to-task communication.

If task *t1* has an entry procedure *p*, then another task *t2* can execute:

t1.p(argument-list);

In order for *p* to execute, *t1* must execute:

accept p (parameter-list);

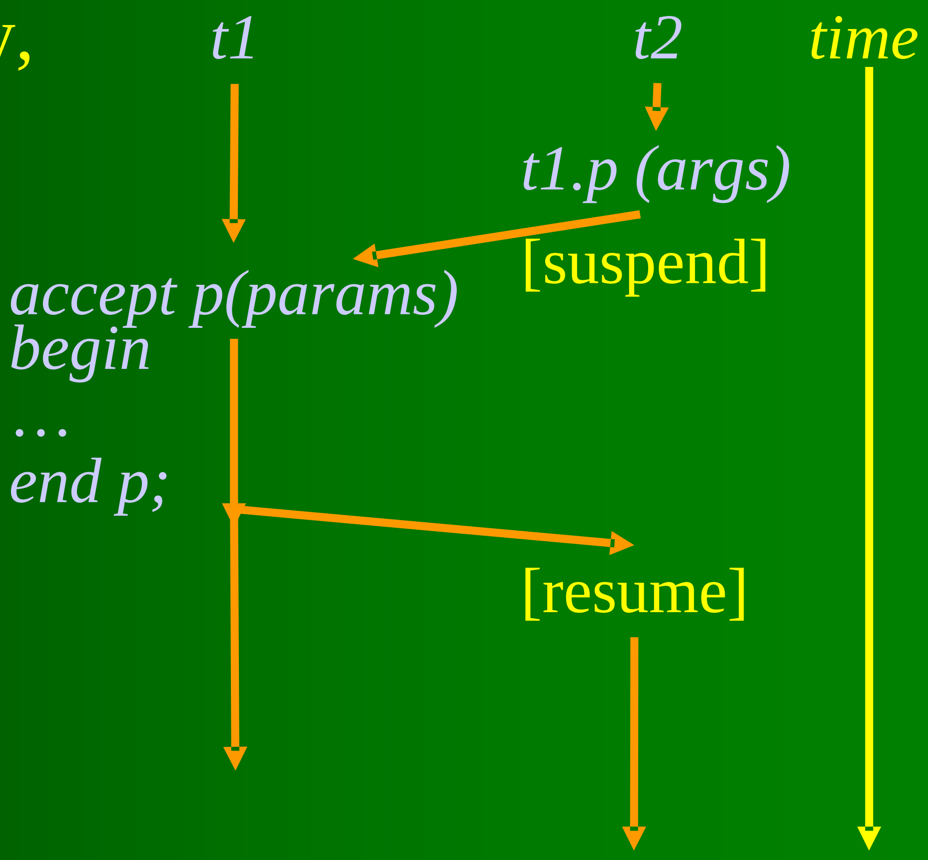
- If *t1* executes *accept p* and *t2* has not called *p*, *t1* must wait for t2;

- If *t2* calls *p* and *t1* has not done *accept p*, *t2* must wait for t1.

Rendezvous

When *t1* and *t2* are both ready, *p* executes:

- *t2's argument-list* is evaluated and passed to *t1.p*'s parameters
- *t2* suspends
- *t1* executes the body of *p*, using its parameter values
- return-values (or *out* or *in out* parameters) are passed back to *t2*
- *t1* continues execution; *t2* resumes execution



This interaction is called a *rendezvous* between *t1* and *t2*.
It does not depend on shared memory, so *t1* and *t2* can be on a uniprocessor, a tightly-coupled or a distributed multiprocessor.

Ada Array Processing

How can we rewrite what's below to complete more quickly?

```
procedure sumArray is
  N: constant integer := 1000000;
  type RealArray is array(1..N) of float;
  anArray: RealArray;

  function sum(a: RealArray; first, last: integer)
                return float is
    result: float := 0.0;
  begin
    for i in first..last loop
      result := result + a(i);
    end loop;
    return result;
  end sum;

begin
  -- code to fill anArray with values omitted
  put( sum(anArray, 1, N) );
end sumArray;
```


Divide-And-Conquer via Tasks

```
procedure parallelSumArray is
  -- declarations of N, RealArray, anArray, Sum() as before …
```

```
task type ArraySliceAdder
   entry SumSlice(Start: in Integer; Stop: in Integer);
   entry GetSum(Result: out float);
end ArraySliceAdder;

task body ArraySliceAdder is
   i, j: Integer; Answer: Float;
begin
 accept SumSlice(Start: in Integer; Stop: in Integer) do
   i:= Start; j:= Stop;                   -- get inputs
 end SumSlice;

 Answer := Sum(anArray, i, j);            -- do the work

 accept GetSum(Result: out float) do
   Result := Answer;                      -- report outcome
 end GetSum;
end ArraySliceAdder;
```

-- continued on next slide…

Divide-And-Conquer via Tasks (ii)

```
-- continued from previous slide …

firstHalfSum, secondHalfSum: Integer;
T1, T2 : ArraySliceAdder;    -- T1, T2 start & wait on accept
begin
  -- code to fill anArray with values omitted

  T1.SumSlice(1, N/2);          -- start T1 on 1st half
  T2.SumSlice(N/2 + 1, N);      -- start T2 on 2nd half

  T1.GetSum( firstHalfSum );    -- get 1st half sum from T1
  T2.GetSum( secondHalfSum );   -- get 2nd half sum from T2

  put( firstHalfSum + secondHalfSum );  -- we're done!

end parallelSumArray;
```

Using two tasks T1 and T2, this *parallelSumArray* version requires roughly 1/2 the time required by *sumArray* (on a multiprocessor).

Using three tasks, the time will be roughly 1/3 the time of *sumArray*.

…

Producer-Consumer in Ada

To give the producer and consumer separate threads, we can define the behavior of one in the 'main' procedure:

and the behavior of the other in a separate task:

We can then build a Monitor-style *Buffer task* with *put()* and *get()* as (auto-synchronizing) entry procedures...

```
procedure ProducerConsumer is
  buf: Buffer;
  it: Item;

    task consumer;
    task body consumer is
      it: Item;
    begin
      loop
        buf.get(it);
        -- consume Item it
      end loop;
    end consumer;

begin -- producer task
  loop
    -- produce an Item in it
    buf.put(it);
  end loop;
end ProducerConsumer;
```

Capacity-1 Buffer

A single-value buffer is easy to build using an Ada *task-type*:

As a *task-type*, variables of this type (e.g., *buf*) will automatically have their own thread of execution.

The body of the task is a loop that accepts calls to *put()* and get() in strict alternation.

```
task type BoundedBuffer1 is
  entry get(it: out Item);
  entry put(it: in Item);
end BoundedBuffer1;

task body BoundedBuffer1 is
  myBuffer: Item;
begin
  loop
    accept put(it: in Item) do
      myBuffer := it;
    end put;

    accept get(it: out Item) do
      it := myBuffer;
    end get;
  end loop;
end BoundedBuffer1;
```

This causes *buf* to alternate between being empty and nonempty.

Capacity-N Buffer

An N-value buffer is a bit more work:

We can accept any call to *get()* so long as we are not empty, and any call to *put()* so long as we are not full.

Ada provides the *select-when* statement to *guard* An *accept*, and perform it if and only if a given condition is *true*

```
-- task declaration is as before …

task body BoundedBuffer is
  N: constant integer := 1024;
  package Buf is new Queue(N, Items);
begin
  loop
    select
      when not Buf.isFull =>
        accept put(it: in Item) do
         Buf.append(it);
        end put;
      or when not Buf.isEmpty =>
        accept get(it: out Item) do
          it := Buf.first;
          Buf.delete;
        end get;
    end select;
  end loop;
end BoundedBuffer;
```

MPI …

… is the *Message Passing Interface*

… is an industry-standard library for distributed-memory parallel computing in C, C++, Fortran, with 3rd party bindings for Java, Python, R, …

… was designed by a large consortium in 1994:

- 12 companies: *Cray*, *IBM*, *Intel*, …
- 11 national labs: *ANL*, *LANL*, *LLNL*, *ORNL*, *Sandia*, …
- representatives from 16 universities

… has "built in" support for many parallel design patterns

… continues to evolve (MPI 2.0 in 1997; 3.0 in 2012; …)

Typical MPI Program Structure

```
#include <mpi.h>                            // MPI functions

int main(int argc, char** argv) {
    int id = -1, numProcesses = -1;

    MPI_Init(&argc, &argv);
    MPI_Comm_size(MPI_COMM_WORLD, &numProcesses);
    MPI_Comm_rank(MPI_COMM_WORLD, &id);

    // program body, which usually includes
    //  calls to MPI_Send() and MPI_Receive()

    MPI_Finalize();
    return 0;
}
```

The 6 MPI Basic Functions

1. **`MPI_Init(&argc, &argv);`**

   \- Set up **`MPI_COMM_WORLD`**, a "communicator"

   (The set of processes that make up the distr. computation)

2. **`MPI_Comm_size(MPI_COMM_WORLD, &numProcesses);`**

   \- How many of us processes are there to attack the problem?

3. **`MPI_Comm_rank(MPI_COMM_WORLD, &id);`**

   -Which of the *n* processes am I?

The 6 MPI Basic Functions (Ct'd)

4. **`MPI_Send(`*`sendAddress, numItems, itemType, destinationID, tag, communicator`*`);`**

   - Send the item(s) at *sendAddress* to *destinationRank*

5. **`MPI_Recv(`*`receiveBuffer, bufferSize, itemType, senderID, tag, communicator, status`*`);`**

   - Receive up to *bufferSize* items from *senderRank*

6. **`MPI_Finalize();`**

   - Shut down distributed computation

These 6 commands are all you need to do useful work!

Other Useful Functions

MPI_Bcast(*receiveBuffer, bufferSize, itemType, senderID, tag, comm, status*);

- Broadcast *bufferSize* items from *senderID* to everyone in *comm*

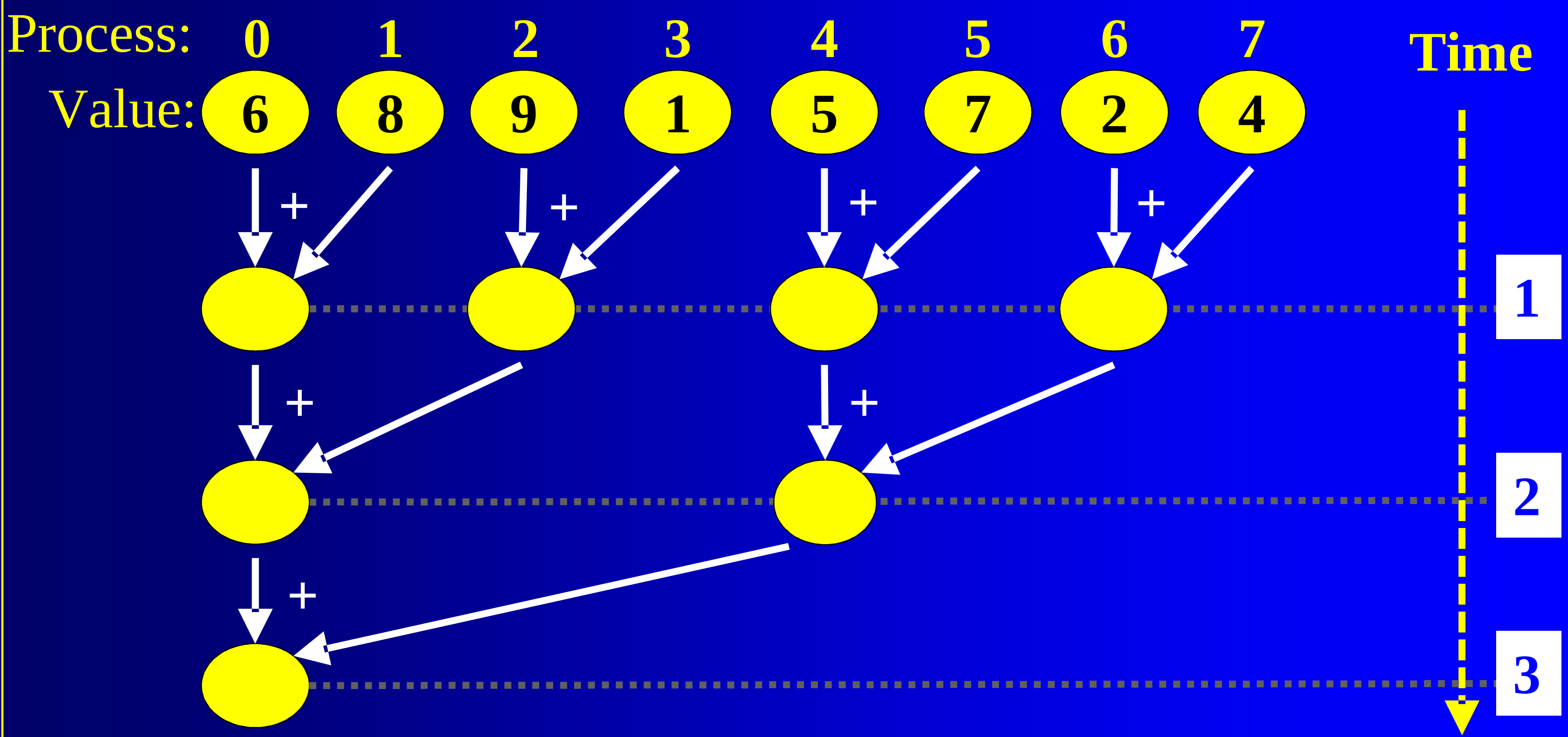
MPI_Reduce(*sendAddress, receiveBuffer, numItems, itemType, combineOp, rootID, tag, comm*);

- Use *combineOp* to combine the distributed items at *sendAddress* into *receiveBuffer* at *rootID0*

These (and many other) commands provide simple but efficient *collective communication*…

Reduction (8 Processes)

To sum the local values of *N* = 8 processes:



Reduction reduces the sum-time from *O(N)* to *O(lg(N))*…

A Very Simple MPI Program

```
#include <iostream>
#include <mpi.h>
using namespace std;

int main(int argc, char** argv) {
    int id = -1, n = -1;

    MPI_Init(&argc, &argv);
    MPI_Comm_size(MPI_COMM_WORLD, &n);
    MPI_Comm_rank(MPI_COMM_WORLD, &id);

    int startValue = id+1;
    int square = startValue * startValue;
    int sumSquares = 0;

    MPI_Reduce(&square, &sumSquares, 1, MPI_INT,
                  MPI_SUM, 0, MPI_COMM_WORLD);

    if (id == 0) {
       cout << "\nThe sum of the squares from 1 to "
             << n << " is " << sumSquares << endl;
    }

    MPI_Finalize();
    return 0;
}
```


MPI Build and Run

To build an MPI C++ *program* from the command line:

mpiCC *program.cpp* –o *program*

To run an MPI *program* from the command line:

mpirun –np *N* –machinefile *hostFile* ./*program*

Launch *N* processes
(each will get a unique rank)
Vary *N* to test scalability

Each process runs
this same *program*
(SPMD pattern)

Launch those *N* processes
on the computers listed in *hostFile*
(optional …)

Testing sumSquares

```
$ mpirun -np 1 ./sumSquares
The sum of the squares from 1 to 1 is 1


$ mpirun -np 2 ./sumSquares
The sum of the squares from 1 to 2 is 5


$ mpirun -np 3 ./sumSquares
The sum of the squares from 1 to 3 is 14


$ mpirun -np 4 ./sumSquares
The sum of the squares from 1 to 4 is 30


$ mpirun -np 128 ./sumSquares
The sum of the squares from 1 to 128 is 707264
```


Summary

- *Concurrent computations* consist of multiple entities:
  - *Processes* in Smalltalk, MPI
  - *Tasks* in Ada
  - *Threads* in C/C++, C#, Java, Go, Python, Ruby, Scala, …
- On a shared-memory multiprocessor:
  - The *Semaphore* was the first synchronization primitive
    - *Java* provides a *Semaphore* class for synchronizing processes
  - *Locks* and *condition variables* separate a semaphore's mutual-exclusion usage (locks) from its synchronization usage (c.v.s)
  - *Monitors* are higher-level, self-synchronizing objects
    - *Java* classes have an associated (simplified) monitor
- On a distributed system:
  - *Ada* tasks provide self-synchronizing *entry procedures*
  - *Erlang, Scala, MPI* support message-passing between processes

Summary (ii)

Comparing Monitors and Tasks/Threads (and Coroutines):

	Has Its Own Thread	Has Its Own Execution State
Monitor	NO	NO
Task/Thread	YES	YES
Coroutine	NO	YES

A *coroutine* (Simula, Lua) is two or more procedures that *share a single thread*, each exercising mutual control over the other:

```
procedure A;
begin
-- do something
resume B;
-- do something
resume B;
-- do something
-- …
end A;
```

```
procedure B;
begin
-- do something
resume A;
-- do something
resume A;
  -- …
end B;
```

