DataFlow Architectures / Languages (1975)

Kahn Process Networks (1974)

Communicating Sequential Processes (CSP) (1978)

Actor Model (1973/1978)

Message Passing Interface (MPI) (1992)

OTHER MESSAGE PASSING COMPUTE MODELS AND FRAMEWORKS

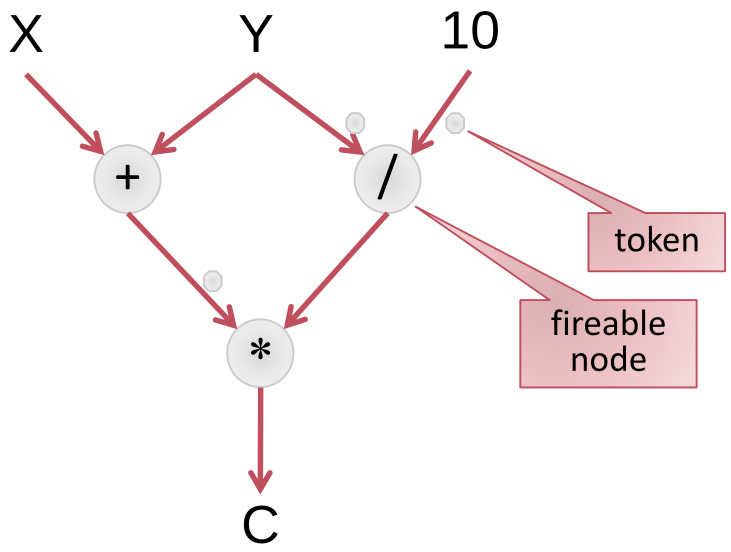
Dataflow Architectures and Languages*

- Take advantage of massive parallelism.
- Von Neumann Architecture unsuitable for parallelism. Bottlenecks:
  - Global program counter and
  - Global updatable memory
- Alternative proposal: dataflow architecture
  - Local memory
  - Execute instructions as soon as operands are available
  - Program in a dataflow computer is a directed graph and data flows between instructions along its edges

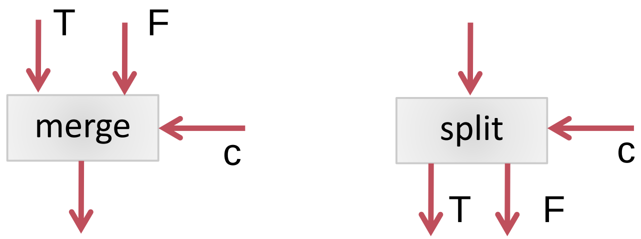
*following „Advances in Dataflow Programming Languages“, Johnston, Hanna, Millar, ACM Computing Surveys Vol36, No.1, 2004
Dataflow Programming Languages invented in the mid 1970s

Example

- A := X + Y
- B := Y / 10
- C := A * B



special control nodes (gates):

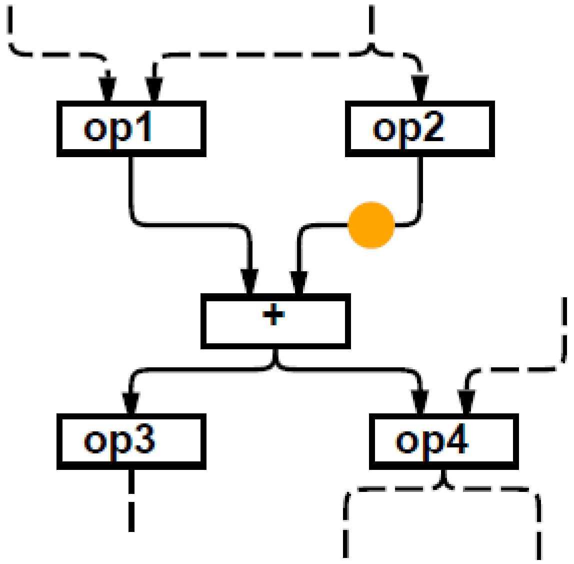


Early Dataflow Hardware Architectures

- Static Architecture (Dennis /Misunas 1975)
  - Each arc can hold only one token
  - Firing rule: token available on all input nodes and no token on output nodes
  - Single token per arc → second loop cannot begin until the previous one has ended – parallelism boils down to pipelining
- Dynamic Architecture (Watson/Gurd 1979)
  - Multiple incovations of a subgraph allowed
  - Each arc a bag of tokens with different tags (destinations, value)
  - Node fireable when on each input edge the same tag is available
  - Can take full advantage of pipelining and out of order execution.

MIT Tagged Token Dataflow Architecture

Conceptual



Encoding of graph

Program memory:

Address	Opcode	Destination(s)
109	op1	120L
113	op2	120R
120	+	141, 159L
141	op3	...
159	op4	... , ...

Encoding of token:

A "token" contains

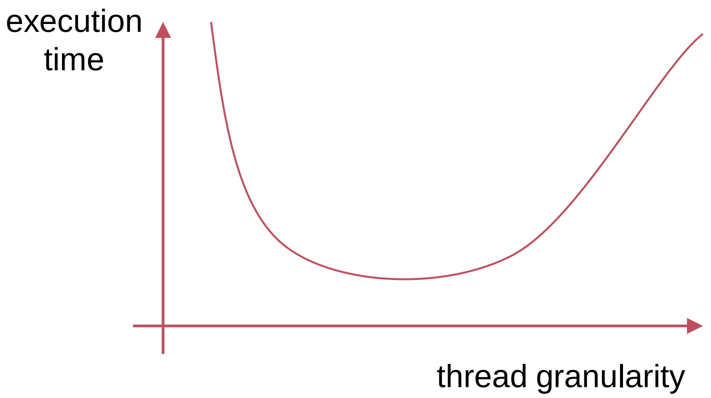
120R, 6.847 — Destination instruction address, Left/Right port, Value

Possible reasons for the failure of early dataflow

- Totally new programming paradigm not accepted
- Dataflow languages almost invariably functional
- Programs in imperative languages hard to compile to a dataflow architecture
- Dataflow architecture operated on a too fine grained level
  - Von Neumann: *process* level granularity
  - Early dataflow: *instruction* level granularity

Hybrid Dataflow

Realization in the 1990s:
Dataflow and von Neumann architectures are not mutually exclusive but the two extremes of a continuum of possible computer architectures



→ Large-grain dataflow: each node contains an entire function expressed in a sequential language

Kahn Process Networks

- Seminal Paper „The Semantics of a Simple Language for Parallel Programming“ by Gilles Kahn, 1974.
- „Formal approach to the design of programming languages and system programming“
- Programming language based on Algol.

- KPNs describe a signal processing system:
  Processes communicate by passing data tokens through unidirectional FIFO channels
- KPN provide a distributed model of computation
- KPNs consist of a set of arbitrary deterministic sequential processes

Concepts

- Channels
- Processes
- Wait
  (***Blocking*** Receive)
- Send
  (Non-Blocking, unbounded fifos)
- Parallel invocation of processes in program body

```
    Begin
(1) Integer channel X, Y, Z, T1, T2 ;
(2) Process f(integer  in U,V; integer out W) ;
     Begin integer I ; logical B ;
           B := true ;
           Repeat Begin
(4)             I := if B then wait(U) else wait(V) ;
(7)             print (I) ;
(5)             send I on W ;
                B := ¬B ;
                end ;
     End ;
    Process g(integer in U ; integer out V, W) ;
     Begin integer I ; logical B ;
       B := true ;
       Repeat Begin
         I := wait (U) ;
         if B then send I on V else send I on  W ;
         B := ¬B ;
         End ;
     End ;
(3) Process h(integer in U;integer out V; integer INIT);
     Begin integer I ;
       send INIT on V ;
       Repeat Begin
         I := wait(U) ;
         send I on V ;
         End ;
     End ;
    Comment : body of mainprogram ;
(6) f(Y,Z,X) par g(X,T1,T2) par h(T1,Y,0) par h(T2,Z,1
    End ;
```

Fig.1. Sample parallel program S.

Determinism

Execution Model

- Channels are the only way for communication
- Communication for each line takes unpredictable but finite time
- Each process is either computing or waiting on ***one*** of its input lines.Processes are not allowed to test input channels for existence of tokens without consuming them (reads are blocking)
- Each process is a sequential process (given a specific input history for a process, the process must be determinstic). Timing / execution order may not influence the result

→ Determinism

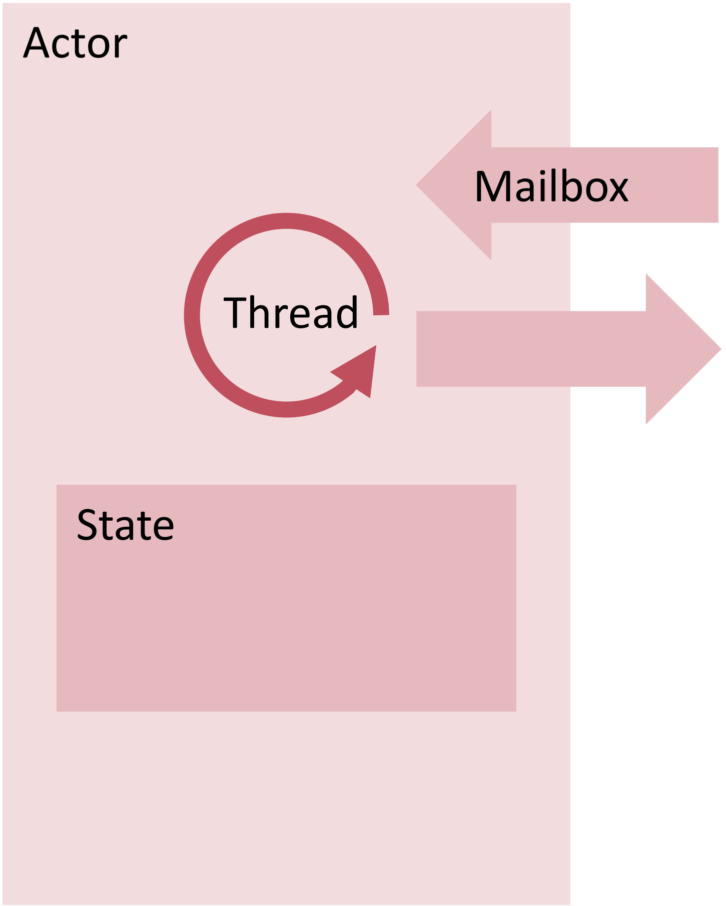
- The history of tokens produced on communication channel does not depend on execution order
- Every execution order that obeys the semantic of the process network produces the same result

The Actor Model*

Actor = Computational agent that maps communication to

- a finite set of communications sent to other actors (messages)
- a new behavior (state)
- a finite set of new actors created (dynamic reconfigurability)

- Undefined global ordering
- Asynchronous Message Passing
- Invented by Carl Hewitt 1973**



*Gul Agha (1986). Actors: A Model of Concurrent Computation in Distributed Systems. Doctoral Dissertation. MIT Press
**Carl Hewitt; Peter Bishop and Richard Steiger (1973). *A Universal Modular Actor Formalism for Artificial Intelligence*. IJCAI.

The Actor Model

Actor model provides a dynamic interconnection topology

- dynamically configure the graph during runtime (add channels)
- dynamically allocate resources

An actor sends messages to other actors using "direct naming", without indirection via port / channel / queue / socket (etc.)

Implemented in various languages such as Erlang, Scala, Ruby and in frameworks such as Akka (for Scala and Java)

Example: Erlang

Functional Programming Language

- code might look unconventional at first

Developed by Ericsson for distributed fault-tolerant applications

- if no state is shared, recovering from errors becomes much easier

Open source

Concurrent, follows the actor model

```
-module(pingpong).
-export([start/1,  ping/2, pong/0]).

ping(0, Pong_Node) ->
    {pong, Pong_Node} ! finished,
    io:format("ping finished~n", []);

ping(N, Pong_Node) ->
    {pong, Pong_Node} ! {ping, self()},
    receive
        pong ->
            io:format("Ping received pong~n", [])
    end,
    ping(N - 1, Pong_Node).

pong() ->
    receive
        finished ->
            io:format("Pong finished~n", []);
        {ping, Ping_PID} ->
            io:format("Pong received ping~n", []),
            Ping_PID ! pong,
            pong()
    end.

start(Ping_Node) ->
    register(pong, spawn(tut18, pong, [])),
    spawn(Ping_Node, tut18, ping, [3, node()]).
```

Erlang example

```
Start() ->
      Pid = spawn(fun() -> hello() end),

      Pid ! Hello,
      Pid ! bye.

hello() ->
      receive
          hello ->
             io:fwrite("Hello world\n"),
                 hello();
          bye ->
            io:fwrite("Bye cruel world\n"),
                     ok
      end.
```

new task (actor) that will execute the hello function
spawn returns address (Pid) of new task

Address (Pid) can be used to send messages to task

Erlang example

```
Start() ->
        Pid = spawn(fun() -> hello() end),

        Pid ! Hello,
        Pid ! bye.

hello() ->
        receive
             hello ->
                io:fwrite("Hello world\n"),
                    hello();
             bye ->
               io:fwrite("Bye cruel world\n"),
                          ok
        end.
```

new task (actor) that will execute the hello function
spawn returns address (Pid) of new task

Address (Pid) can be used to send messages to task

Messages sent to a task are put in a mailbox

Receive reads the first message in the mailbox, which is matched against patterns (similar to a switch statement)

Event-driven programming:
code is structured as reactions to events

Communicating Sequential Processes

Sir Charles Antony Richard Hoare (aka C.A.R. / Tony Hoare) (1978, 1985)

Formal language defining a process algebra for concurrent systems.

Operators seq (sequential) and par (parallel) for the hierarchical composition of processes.

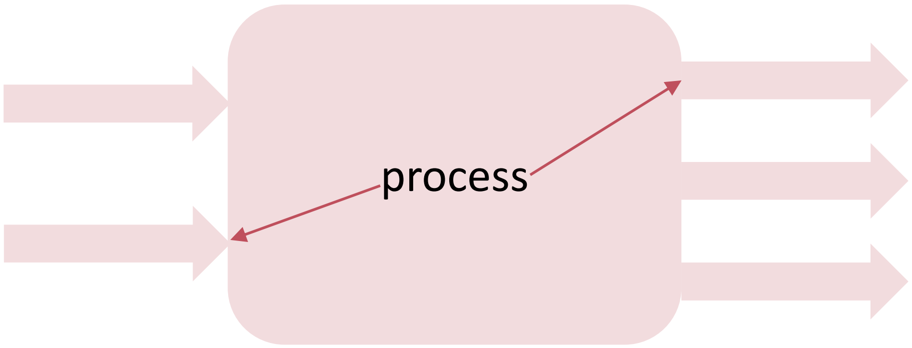
Synchronisation and Communication between parallel processes with Message Passing.

- Symbolic channels between sender and receiver
- Read and write requires a rendevouz (synchronous!)

CSP was firstly implemented in Occam.

CSP: Indirect Naming

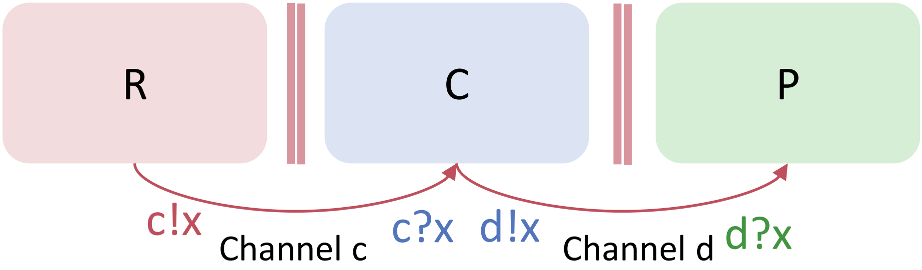
- Most message passing architectures (including CSP) include an intermediary entity (*port / channel*) to address send destination
- Process issuing send() specifies the port to which the message is sent
- Process issuing receive() specifies a port number and waits for the first message that arrives at the port



CSP Example (from Hoare's seminal Paper)

Conway's Problem

- Write a program that transforms a series of cards with 80-character columns in a series of printing lines with 125 characters each. Replace each "**" by "^"
- Separation into processes (Threads)
  `R par C par P`
  - R: Reading process reading 80-character records
  - C: Converting process converting "**" into "^"
  - W: Writing process: write records with 125 characters



CSP Example (from Hoare's seminal Paper)

[west :: DISASSEMBLE] || **X :: SQUASH** || east :: ASSEMBLE]

SQUASH

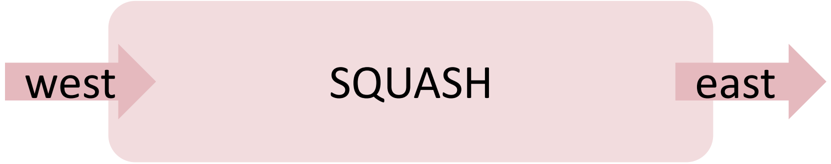
```
X ::
*[c:character; west?c →
        [c # asterisk → east!c
        |c = asterisk → west?c;
                [c # asterisk → east!asterisk; east!c
                |c = asterisk → east!upward arrow
                ]
        ]
]
```

Repetition of guarded command

Guarded receive

Blocking send

Guarded alternatives



OCCAM

First programming language to implement CSP (1983)

```
ALT
  count1 < 100 & c1 ? data
    SEQ
      count1 := count1 + 1
      merged ! data
  count2 < 100 & c2 ? data
    SEQ
      count2 := count2 + 1
      merged ! data
  status ? request
    SEQ
      out ! count1
      out ! count2
```

Superpascal (Per Brinch Hansen (1994))

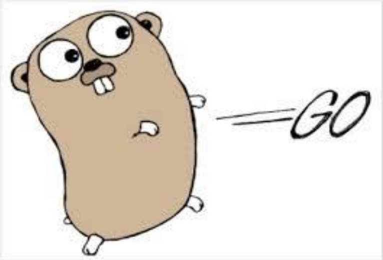
Typed channels, processes, parallel statements, message passing

```
type channel= *(boolean, number);

procedure ring(a: number; var prime: boolean);
var left, right: channel;
begin
  open(left, right);
  parallel
  pipeline(left, right) | master(a, prime, left, right)
  end
end;

procedure node(i: integer;
        left, right: channel);
var a: number; j: integer;
        composite: boolean;
begin
        receive(left, a);
        if i < p then send(right, a);
        test(a, i, composite);
        send(right, composite);
        for j := 1 to i - 1 do
        begin
                receive(left, composite);
                send(right, composite)
        end
end;
```

```
procedure master(
        a: number; var prime: boolean;
        left, right: channel);
var
        i: integer; composite: boolean;
begin
        send(left, a); prime := true;
        for i := 1 to p do
                begin
                        receive(right, composite);
                        if composite then
                                prime := false
                end
end;

procedure pipeline(left, right: channel);
        type row = array [0..p] of channel;
        var c: row; i: integer;
begin
        c[0] := left; c[p] := right;
        for i := 1 to p ¡ 1 do
                open(c[i]);
        forall i := 1 to p do
                node(i, c[i-1], c[i])
end;
```

Go programming language

Concurrent programming language from Google



Language support for:

- Lightweight tasks (called goroutines)
- Typed channels for task communications
  - channels are synchronous (or unbuffered) by default
  - support for asynchronous (buffered) channels

Inspired by CSP

Language roots in Algol Family: Pascal, Modula, Oberon [Prof. Niklaus Wirth, ETH]

[One of the inventors of Go: Robert Griesemer holding a PhD from ETH]

Go example

```go
func main() {

	msgs := make(chan string)
	done := make(chan bool)

	go hello(msgs,done);

	msgs <- "Hello"
	msgs <- "bye"

	ok := <-done

	fmt.Println("Done:", ok);
}
```

```go
func hello(msgs chan string,
           done chan bool) {

	for {
		msg := <-msgs
		fmt.Println("Got:", msg)

		if msg == "bye" {
			break
		}
	}

	done <- true;
}
```

Go example

```
func main() {

        msgs := make(chan string)
        done := make(chan bool)

        go hello(msgs,done);

        msgs <- "Hello"
        msgs <- "bye"

        ok := <-done

        fmt.Println("Done:", ok);
}
```

Create two channels:
- msgs: for strings
- done: for boolean values

```
func hello(msgs chan string,
           done chan bool) {

        for {
                msg := <-msgs
                fmt.Println("Got:", msg)

                if msg == "bye" {
                        break
                }
        }

        done <- true;
}
```

Go example

```
func main() {

        msgs := make(chan string)
        done := make(chan bool)

        go hello(msgs,done);

        msgs <- "Hello"
        msgs <- "bye"

        ok := <-done

        fmt.Println("Done:", ok);
}
```

Create a new task (goroutine), that will execute function `hello` with the given arguments

```
func hello(msgs chan string,
           done chan bool) {

       for {
              msg := <-msgs
              fmt.Println("Got:", msg)

              if msg == "bye" {
                     break
              }
       }

       done <- true;
}
```

Go example

Hello takes two channels as arguments for communication

```
func main() {

        msgs := make(chan string)
        done := make(chan bool)

        go hello(msgs,done);

        msgs <- "Hello"
        msgs <- "bye"

        ok := <-done

        fmt.Println("Done:", ok);
}
```

```
func hello(msgs chan string,
           done chan bool) {

       for {
               msg := <-msgs
               fmt.Println("Got:", msg)

               if msg == "bye" {
                       break
               }
       }

       done <- true;
}
```

Go example

```go
func main() {

	msgs := make(chan string)
	done := make(chan bool)

	go hello(msgs,done);

	msgs <- "Hello"
	msgs <- "bye"

	ok := <-done

	fmt.Println("Done:", ok);
}
```

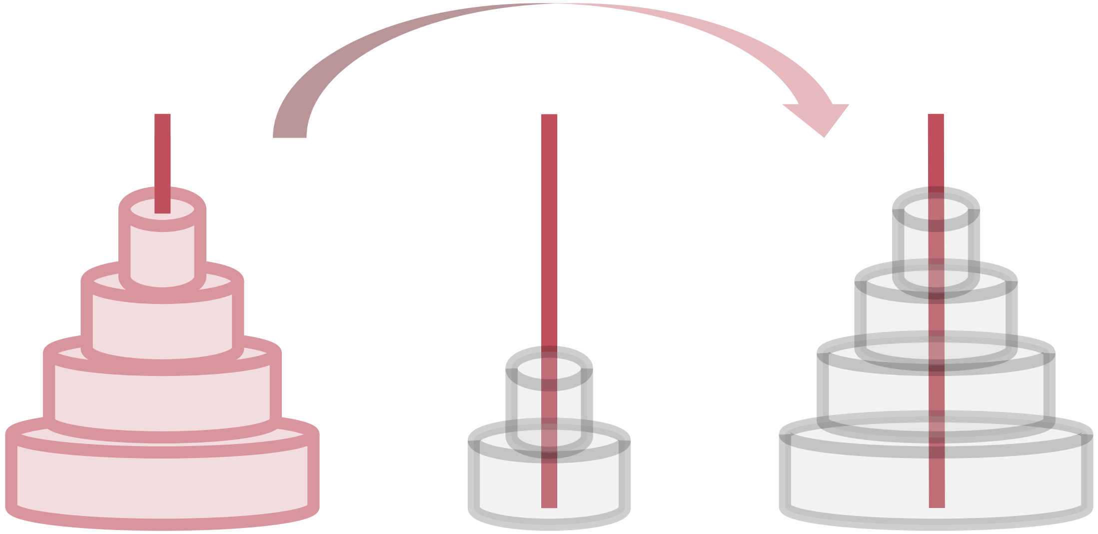
Write arguments to msgs channel

Read result via done channel

```go
func hello(msgs chan string,
           done chan bool) {

	for {
		msg := <-msgs
		fmt.Println("Got:", msg)

		if msg == "bye" {
			break
		}
	}

	done <- true;
}
```

Towers of Hanoi (sequential)

```
package main
import "fmt"

func Hanoi(n, f, t, u int) {
        if n<=1 {
                fmt.Println(f, "->", t)
        } else{
                Hanoi(n-1, f, u, t);
                fmt.Println(f, "->", t);
                Hanoi(n-1, u, t, f);
        }
}

func main() {
        Hanoi(4,1,3,2)
}
```

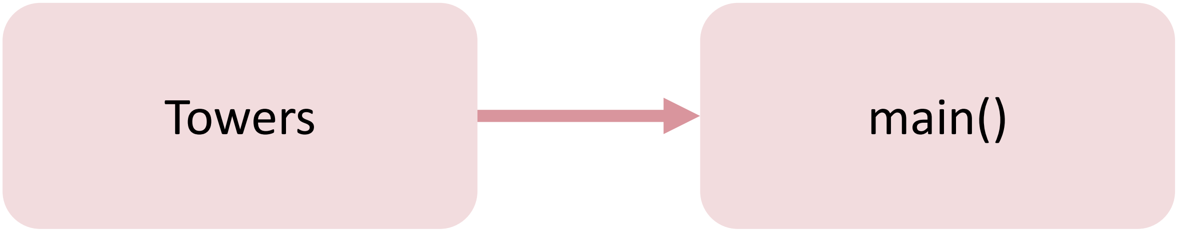


Q: How can I easily return the moves in this sequence to main()?

Towers of Hanoi with go-routine

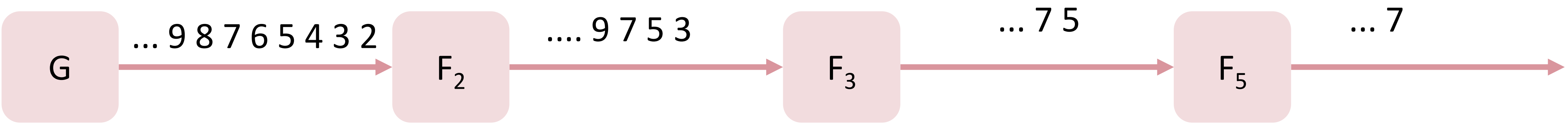
```
func Hanoi(ch chan<- int, n, f, t, u int) {
    if n<=1 {
        ch <- f
        ch <- t
    } else{
        Hanoi(ch, n-1, f, u, t);
        ch <- f
        ch <- t
        Hanoi(ch, n-1, u, t, f);
    }
}

func Towers(ch chan<- int, n, f, t, u int) {
    Hanoi(ch,n,f,t,u);
    ch <- -1
}
```

```
func main() {
    ch := make(chan int)
    go Towers(ch, 4,1,3,2)
    for ;; {
        i := <-ch
        if i<0 {return}
        j := <-ch
        fmt.Println(i,"<-",j)
    }
}
```



Concurrent prime sieve

Each station removes multiples of the first element received and passes on the remaining elements to the next station



source code copied from golang.org

Concurrent prime sieve

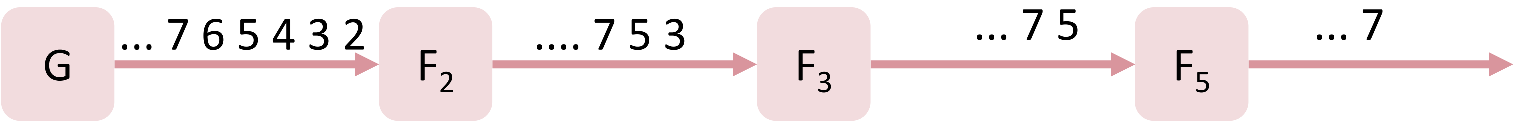
```
func Generate(ch chan<- int) {
    for i := 2; ; i++ {
        ch <- i
    }
}
```

G

```
func Filter(in <-chan int, out chan<- int, prime int) {
    for {
        i := <-in  // Receive value from 'in'.
        if i%prime != 0 {
            out <- i // Send 'i' to 'out'.
        }
    }
}
```

F_{prime}

```
func main() {
    ch := make(chan int)
    go Generate(ch)
    for i := 0; i < 10; i++ {
        prime := <-ch
        fmt.Println(prime)
        ch1 := make(chan int)
        go Filter(ch, ch1, prime)
        ch = ch1
    }
}
```



source code copied from golang.org

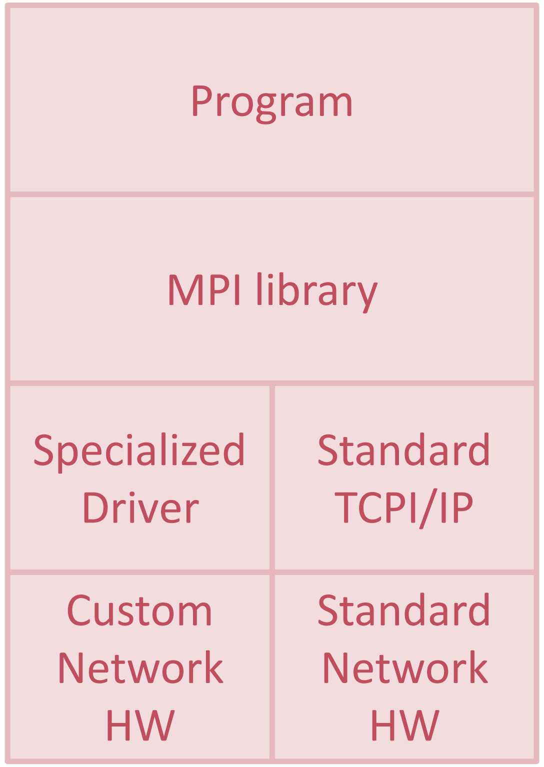
Message Passing Interface (MPI)

Message passing **libraries**:

- PVM (Parallel Virtual Machines) 1980s
- **MPI** (Message Passing Interface) 1990s

MPI = Standard API

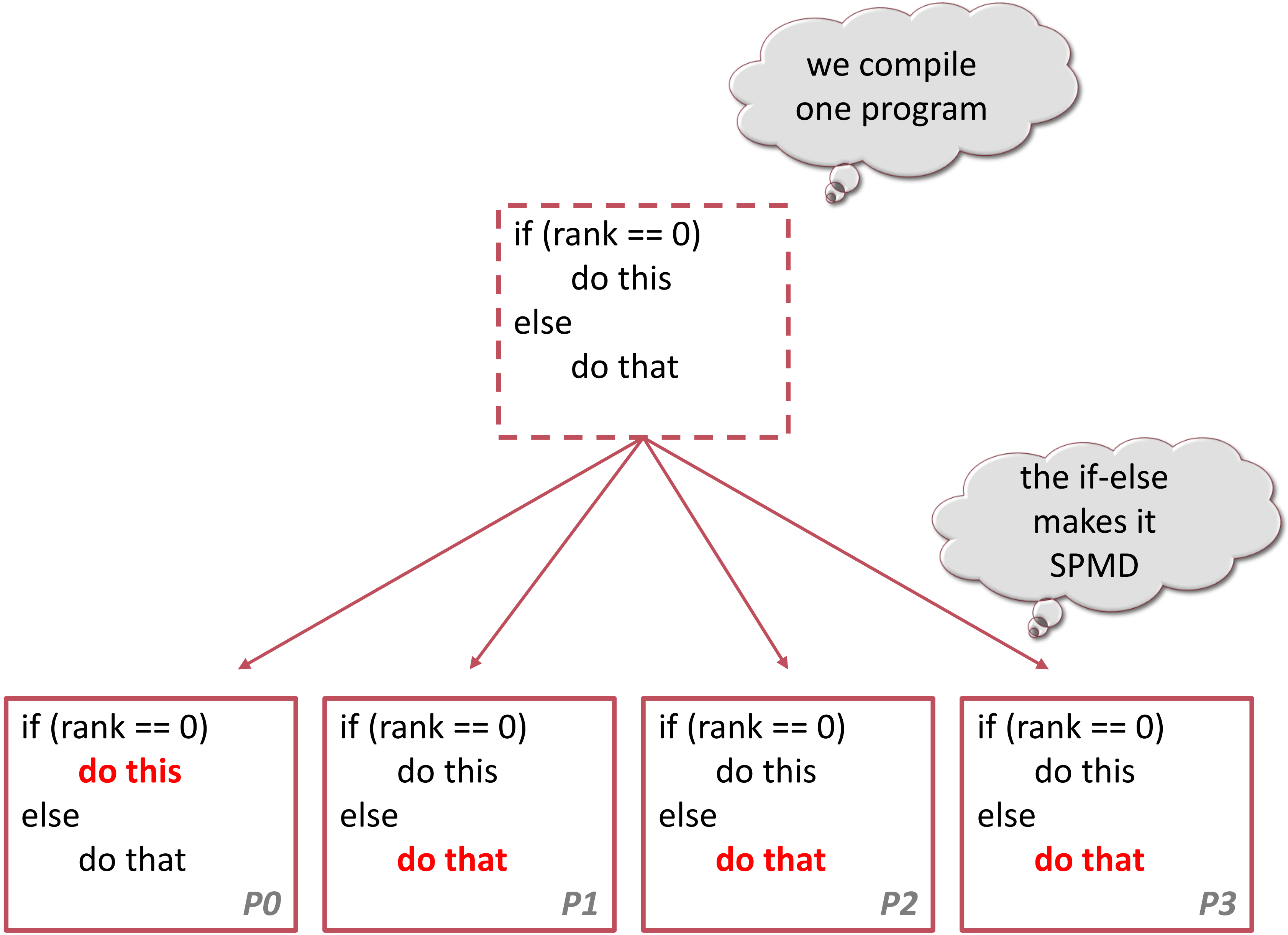
- Hides Software/Hardware details
- Portable, flexible
- Implemented as a library



SPMD

Single **P**rogram

Multiple **D**ata
(Multiple Instances)



Synchronous / Asynchronous vs Blocking / Nonblocking

Synchronous / Asynchronous

- about communication between sender and receiver

Blocking / Nonblocking

- about local handling of data to be sent / received

MPI Send and Receive Defaults

Send

- blocking,
- synchrony **implementation dependent**
  - depends on existence of buffering, performance considerations etc

Danger of Deadlocks.
Don’t make any assumptions!

Receive

- blocking

There are a lot of different variations of this in MPI.

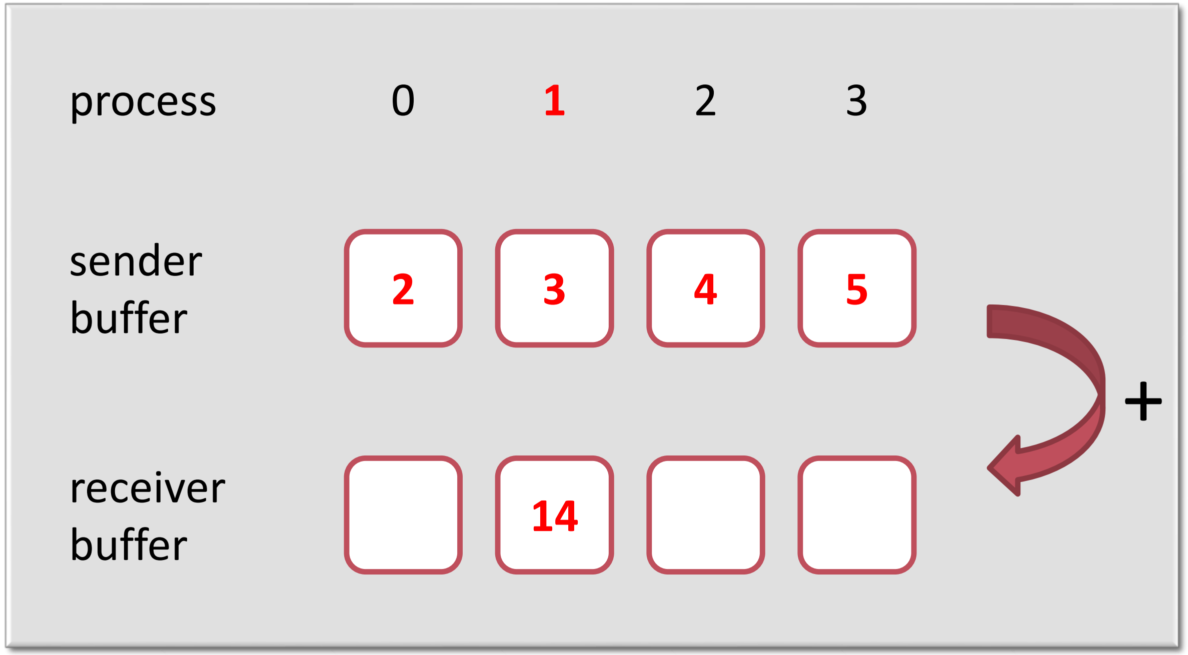
Group Communication

MPI supports sending messages between groups of processors

- not absolutely necessary for programming
- but essential for performance

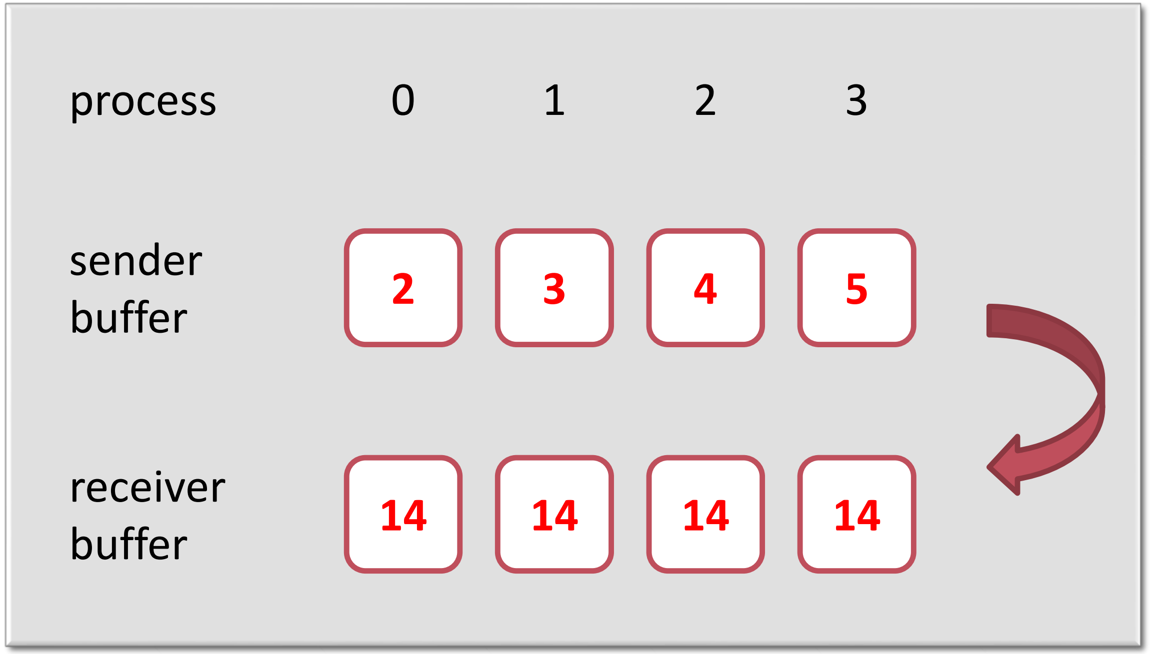
Examples: broadcast, gather, scatter, reduce, barrier

Reduce

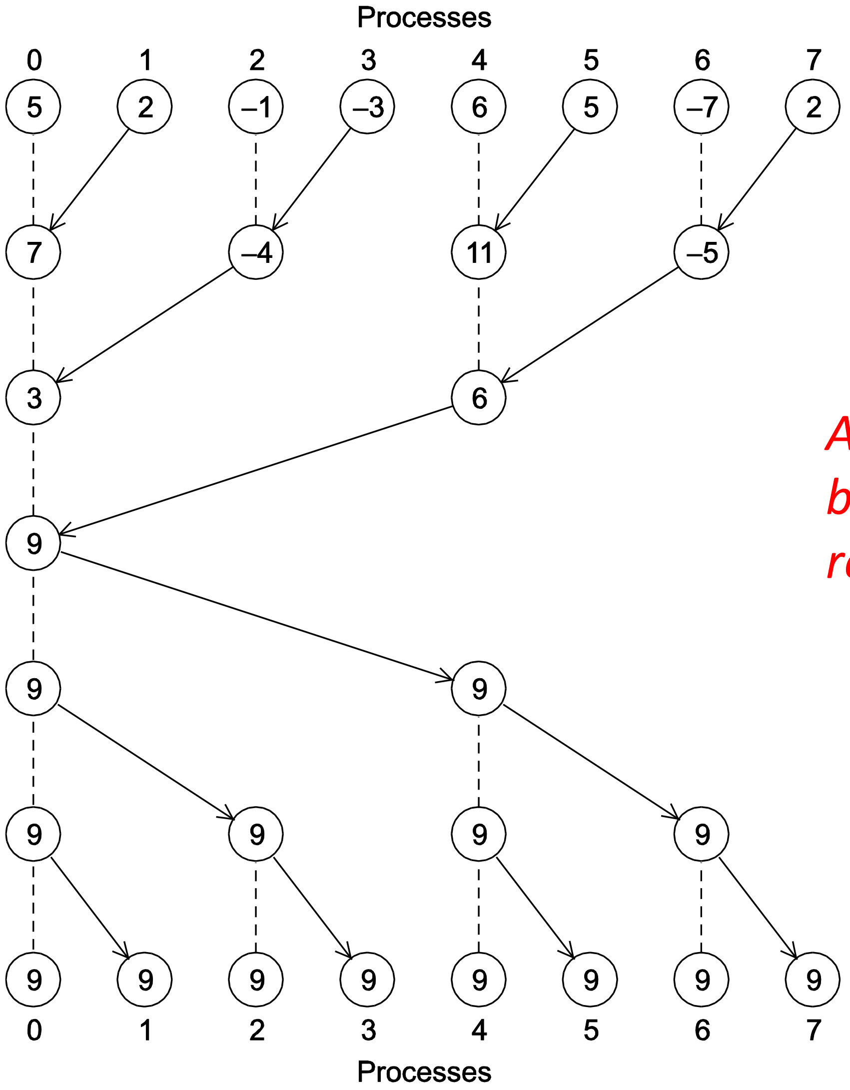


Allreduce

Useful in a situation in which all of the processes need the result of a global sum in order to complete some larger computation.

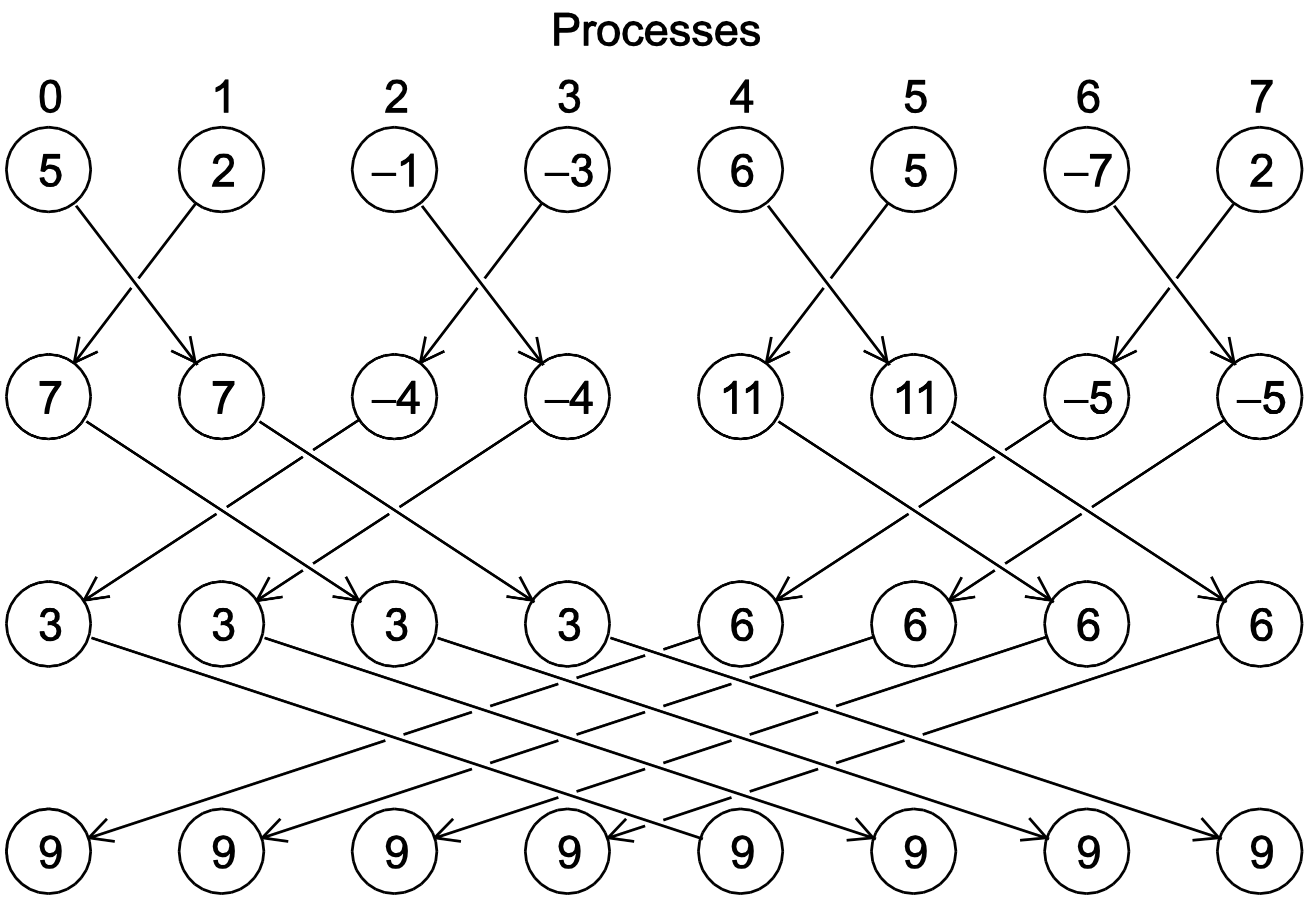


Allreduce = Reduce + Broadcast?



A global sum followed by distribution of the result.

Allreduce ≠ Reduce + Broadcast

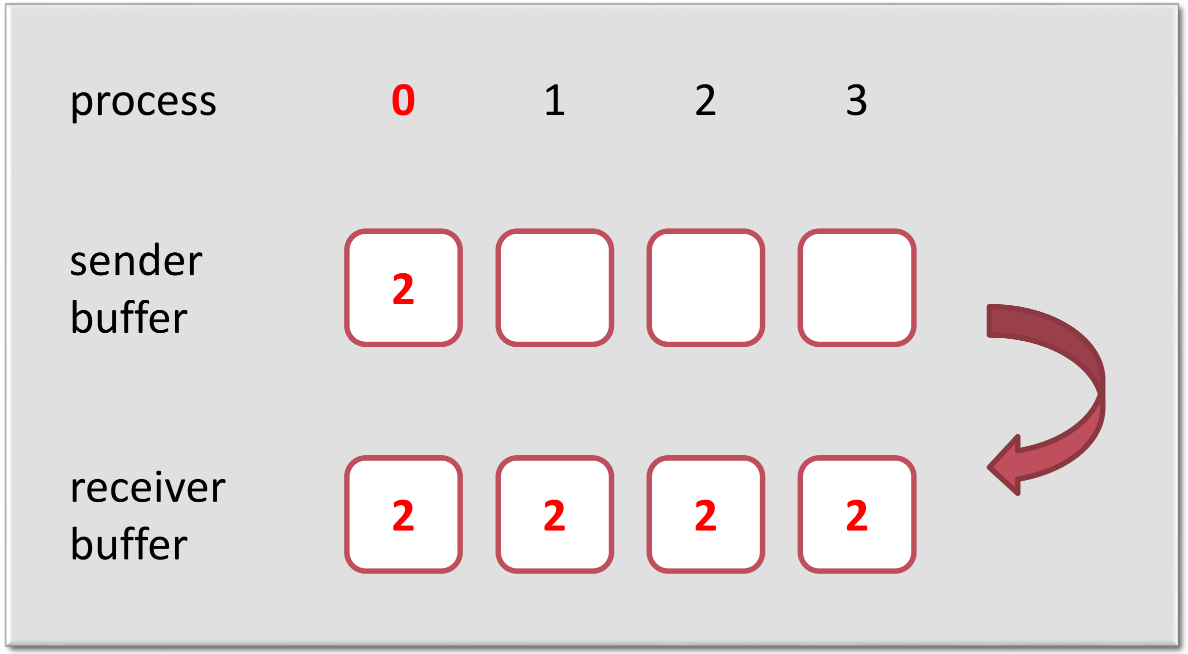


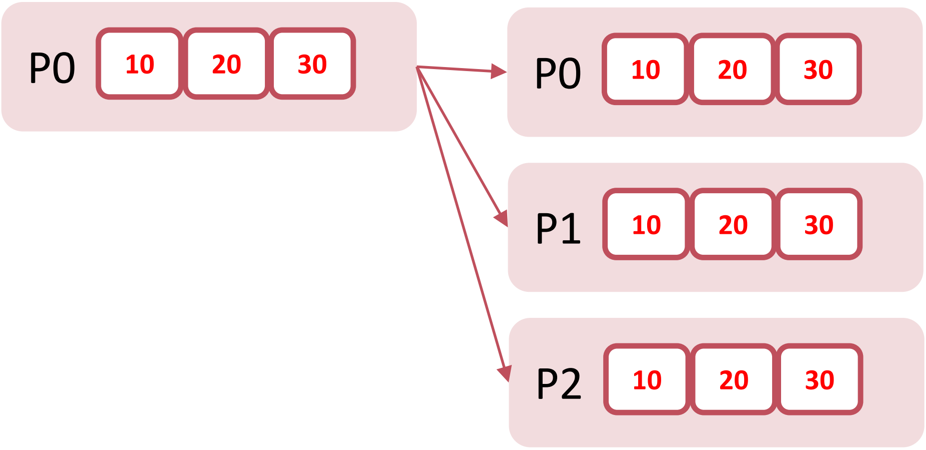
A butterfly-structured global sum.

Broadcast

Data belonging to a single process is sent to all of the processes in the communicator.

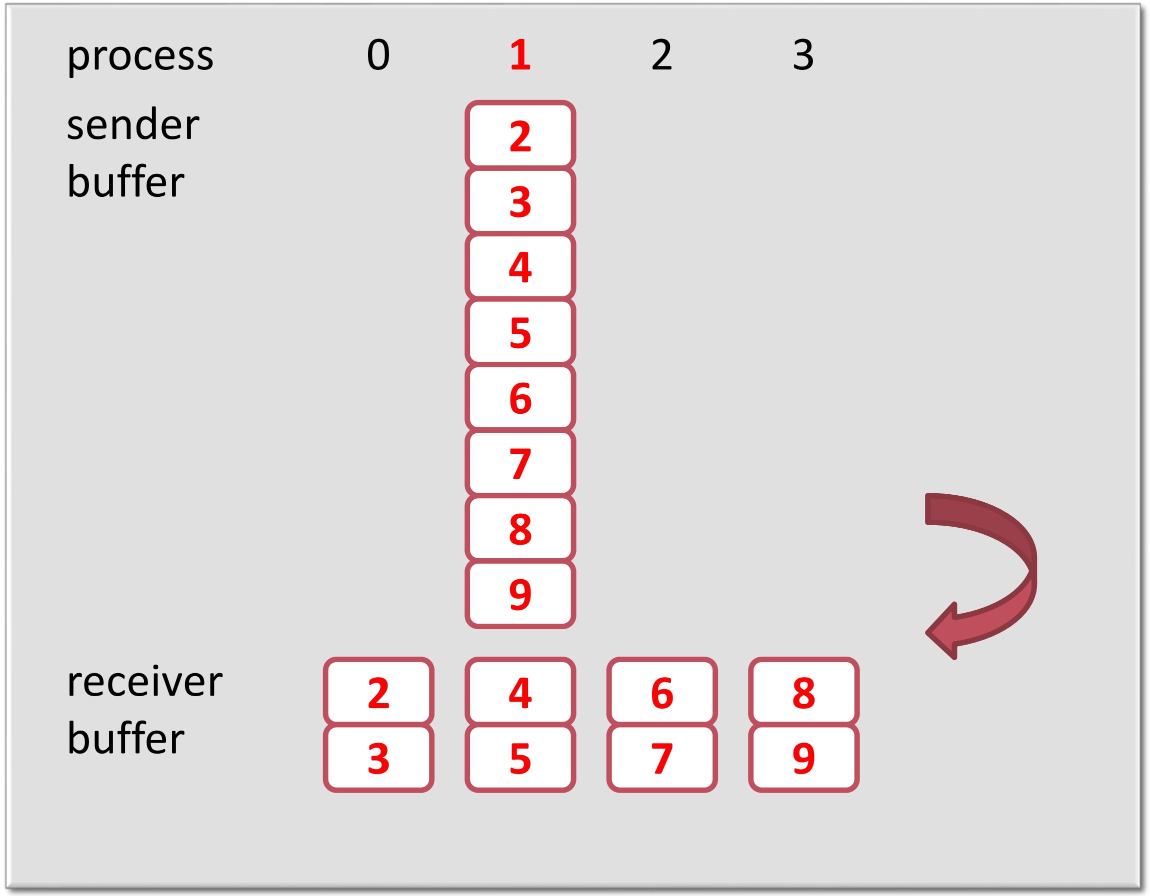
$$y = \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \end{bmatrix} \cdot \begin{bmatrix} \mathbf{10} \\ \mathbf{20} \\ \mathbf{30} \end{bmatrix}$$



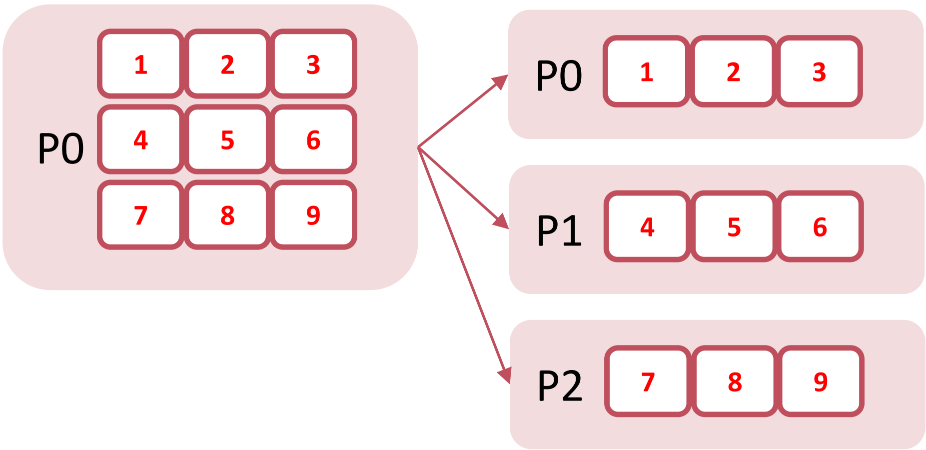


Scatter

Scatter can be used in a function that reads in an entire vector on process 0 but only sends the needed components to each of the other processes.

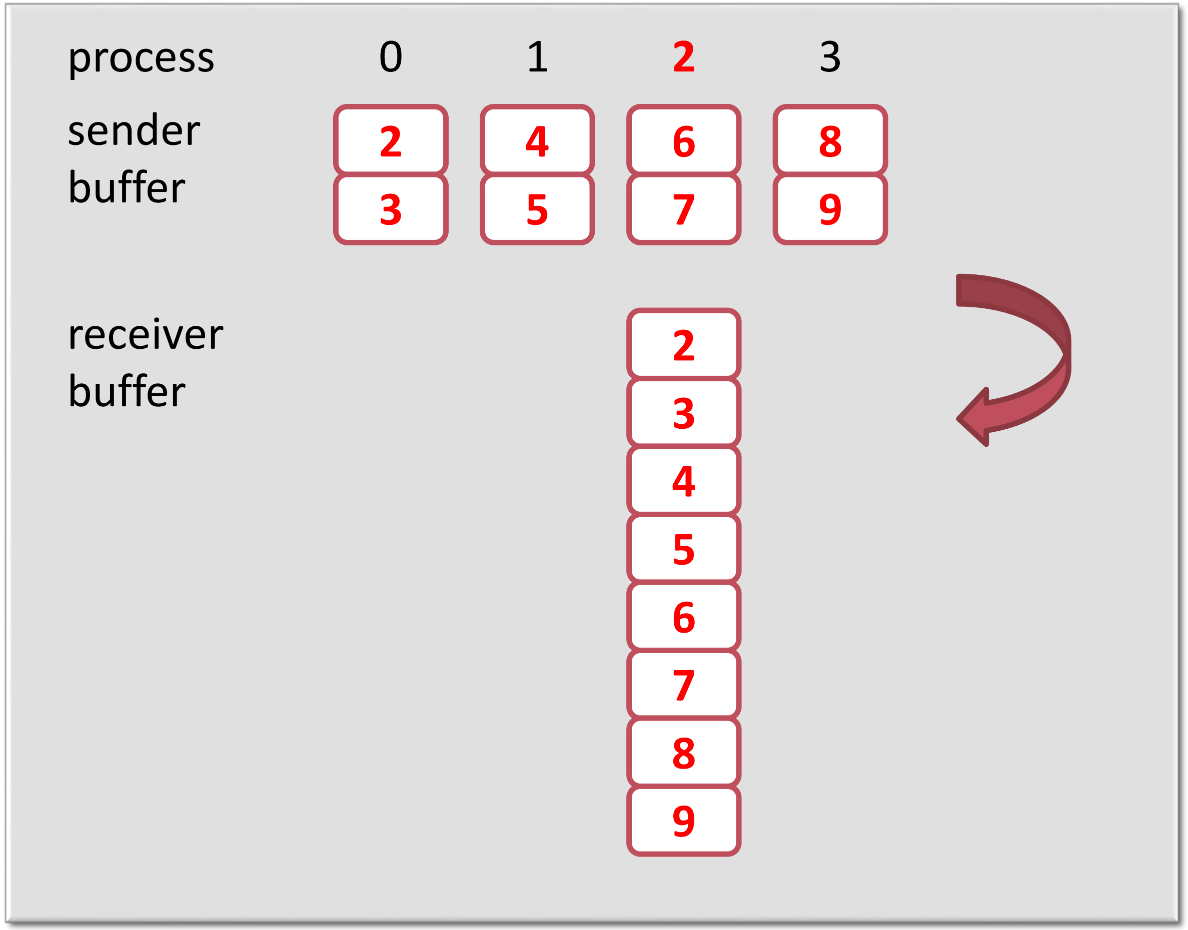


$$y = \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \end{bmatrix} \cdot \begin{bmatrix} 10 \\ 20 \\ 30 \end{bmatrix}$$



Gather

Collect all of the components of the vector onto destination process, then destination process can process all of the components.



$$y = \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \end{bmatrix} \cdot \begin{bmatrix} 10 \\ 20 \\ 30 \end{bmatrix}$$