Message Passing and Channels

Einar Broch Johnsen, S. Lizeth Tapia Tarifa, Eduard Kamburjan, Juliane Päßler

September 26, 2023

University of Oslo

Message Passing

Structure

- Part 1: Shared Memory (and Java)
- **Part 2:** Message Passing (and Go)
- Part 3: Analyses and Tool Support (and Rust)

Content of next part:

- Synchronous and asynchronous message passing
- Channels, actors, go-routines, asynchrounous programming

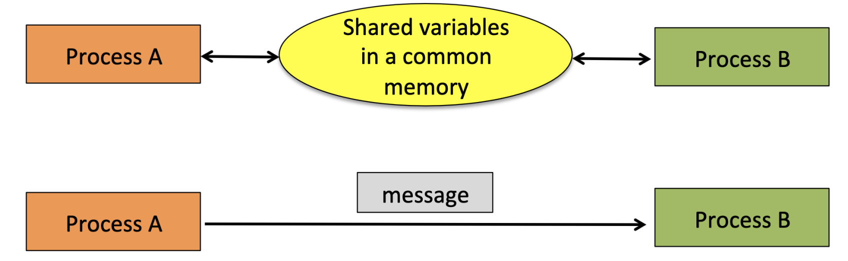
Outline Today

- *Asynchronous message passing*: channels, messages, primitives
- Example: filters and sorting networks
- Comparison of message passing and monitors
- Basics *synchronous message passing*

Concurrent programming: shared state vs. messages

Concurrent programming

- *Concurrent program:* two or more processes that work together to perform a task.
- The processes work together by communicating with each other using:
  - *Shared variables:* One process writes into a variable that is read by another.
  - *Message passing:* One process sends a message that is received by another



Program synchronization - recap

Two kinds of synchronization approaches (regardless of the form of communication)

- Mutual exclusion (mutex)
  - A program mechanism that prevents processes from accessing a shared resource at the same time.
  - Only one process or thread owns the mutex at a time.
- Condition synchronization
  - Delay a process until a given condition is true.
- To prevent race condition: when concurrent processes access and change a shared resource.
- Used for critical section.

Recap

- So far: shared variable programming
- **Now:** Distributed programming

Distributed Systems

Shared memory vs. distributed memory

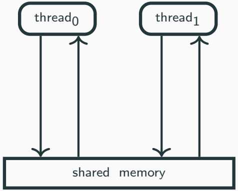
System architectures with shared memory:

- Many processors access the same physical memory
- E.g., laptops, fileservers with many processors on one motherboard

Distributed memory architectures:

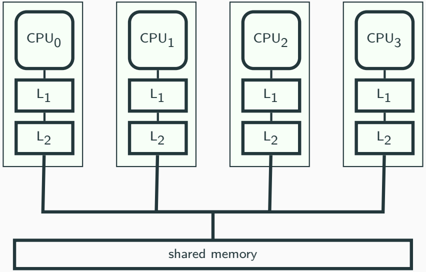
- Each processor has private memory, communication over a connections in a "network"
- examples:
  - Multicomputer: asynchronous multi-processor with distributed memory
  - Workstation clusters: PC's in a local network, NFS (Network File System)
  - Grid system: machines on the Internet, resource sharing
  - cloud computing: cloud storage service
  - NUMA-architectures
  - cluster computing ...

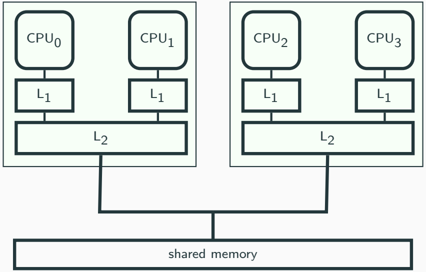
Shared memory concurrency in the real world

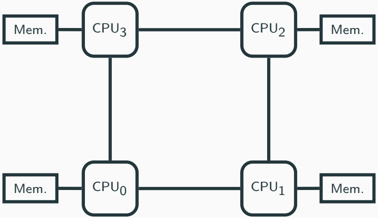


- Shared memory architecture is a simplification
- Out-of-order executions:
  - Due to complex memory hierarchies, caches, buffers,...
  - Due to weak memory, micro-ops, compiler optimizations,...

SMP (symmetric multiprocessing), multi-core architecture, and NUMA







Concurrent vs. distributed programming

Shared-Memory Systems

- Processors share one memory
- Processors communicate via reading and writing of shared variables

Concurrent programming provides primitives to synchronize over memory

Distributed Systems

- Memory is distributed: processes cannot share variables/memory locations
- Processes communicate by sending and receiving *messages* via e.g., shared *channels*,
- or (in future lectures): communication via *RPC* and *rendezvous*

Distributed programming provides primitives to communicate

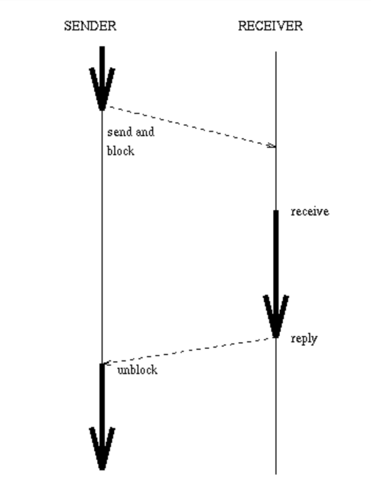
- Some concepts from distributed systems are also useful abstractions for shared memory
- Abstractions can be decoded to different primitives, e.g., channels can shared-memory
- Also: mixed shared-distributed systems

Synchronous and Asynchronous Message Passing

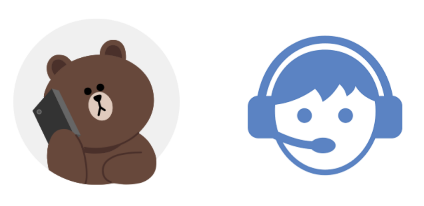
Message Passing

- *Message passing* refers to the sending of a message to a process.
- This message can be used to invoke a process
- Two types of message passing:
    - *Synchronous* message passing
    - *Asynchronous* message passing

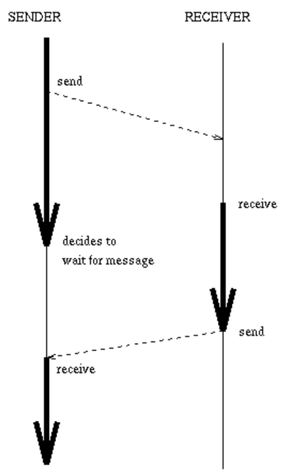
Synchronous message passing - high level concept



Synchronous message passing



Asynchronous message passing - high level concept



Asynchronous message passing

Synchronous vs. asynchronous message passing - trade off

Synchronous message passing	**Asynchronous message passing**
- No memory buffer is required	- Memory buffer is required (memory is cheap)
- Concurrency is reduced	- Have more concurrency
- Programs are more prone to deadlock	- Programs are less prone to deadlock

We will comeback to this comparison later in the lecture.

Channels

Asynchronous message passing: channel abstraction

Channel

Abstraction, e.g., of a physical communication network, for one-way communication between two entities (similar to producer-consumer). For us:

- Unbounded FIFO (queue) of waiting messages
- Preserves message order
- Atomic access
- Error–free
- Typed

Numerous variants exists in different language: untyped, lossy, unnamed, bounded ...

We will look at more complex types later

Asynchronous message passing: primitives

Channel declaration

Await

```
chan c(type1 id1, ..., typeN idN);
```

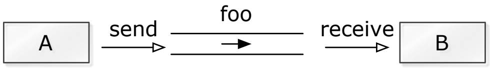
Messages are *n*-tuples of respective types.

Communication Primitives

- `send c(expr1,..., exprN);`
  Non-blocking, i.e. asynchronous: message is sent and process continues its execution
- `receive c(v1,...,vN);`
  Blocking: receiver process waits until message is sent on the channel
  Message stored in variables `v1,...,vN`.
- `empty(c);`
  True if channel is empty

Example: message passing

(x,y) =

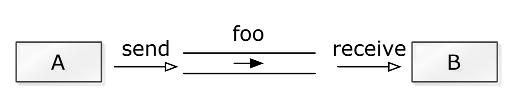


Await

```
chan foo(int);
int x; int y;

process A {
  send foo(1);
  send foo(2);}

process B {
  receive foo(x);
  receive foo(y);}
```

Example: message passing

(x,y) = (1,2)

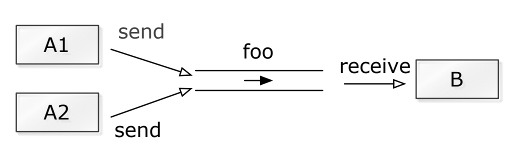


Await

```
chan foo(int);
int x; int y;

process A {
  send foo(1);
  send foo(2);}

process B {
  receive foo(x);
  receive foo(y);}
```

Example: Shared Channel

(x,y) =

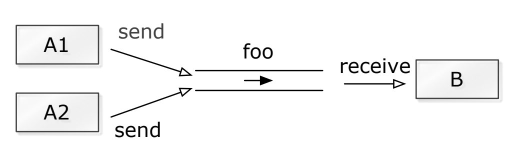


Await

```
process A1 {
  send foo(1); }

process A2 {
  send foo(2); }

process B {
  receive foo(x);
  receive foo(y); }
```

Example: Shared Channel

$(x,y) = (1,2)$ or $(2,1)$



Await

```
process A1 {
  send foo(1); }

process A2 {
  send foo(2); }

process B {
  receive foo(x);
  receive foo(y); }
```

Asynchronous message passing and semaphores

A channel acts as a semaphore, where sending and receiving have the same asymmetry as **V** (increase the value of the semaphore by one) and **P** (wait until value of the semaphore is greater than zero, and then decrease the value by one).

Comparison with general semaphores

channel	$\simeq$	**semaphore**
`send`	$\simeq$	**V**
`receive`	$\simeq$	**P**
Number of messages in queue	$\simeq$	value of semaphore

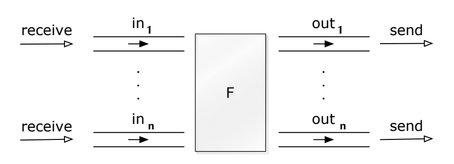
The value of the message plays no role for the semaphore-interpretation.

Filters: one–way interaction

Filters F

A filter **F** is a process which:

- Receives messages on input channels,
- Sends messages on output channels, such that
- the output is a function of the input (and the initial state).



- A filter is specified as a predicate.
- Some computations are naturally seen as a composition of filters:
- cf. stream processing, feedback loops and *dataflow programming*

Example: A single filter process

Task: Sort a list of n numbers into ascending order.

Filter

Process **Sort** with input channels `input` and output channel `output`.

Example implementation: get n over `input`, then read n times from `input` and send the sorted list at once over `output`.

Sort predicate

- n : number of values sent to `output`.
  $sent[i]$: i'th value sent to `output`, $received[j]$: j'th value received in `input`,

$$\forall i : 1 \leq i < n.\ \left(sent[i] \leq sent[i+1]\right) \wedge$$
$$\forall i : 1 \leq i < n.\ \exists j : 1 \leq j < n.\ sent[i] = received[j] \wedge$$
$$\forall i : 1 \leq i < n.\ \exists j : 1 \leq j < n.\ received[i] = sent[j]$$

Filter for merging of streams

Task: Merge two sorted input streams into one sorted stream.

Process `Merge` with input channels $\texttt{in}_1$ and $\mathbf{in}_2$ and output channel `out`:

$$\texttt{in}_1 : \langle 1\ 4\ 9 \ldots \rangle \qquad \texttt{in}_2 : \langle 2\ 5\ 8 \ldots \rangle \qquad \texttt{out} : \langle 1\ 2\ 4\ 5\ 8\ 9 \ldots \rangle$$

Special value **EOS** marks the end of an input, but result should be output online.

Merge predicate

n : number of values sent to out so far, $sent[n]$: i'th value sent to out so far.
The following shall hold when **Merge** *terminates*:

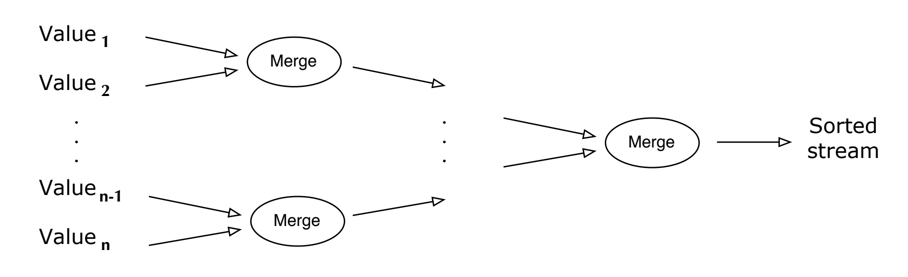
$$\begin{aligned} & \texttt{empty}(\texttt{in}_1) \wedge \texttt{empty}(\texttt{in}_2) \wedge \ sent[n+1] = \textbf{EOS} \\ \wedge \quad & \forall i : 1 \leq i < n \big(sent[i] \leq sent[i+1] \big) \\ \wedge \quad & \text{values sent to out are an } \textit{interleave} \text{ of values from } \texttt{in}_1 \text{ and } \texttt{in}_2 \end{aligned}$$

Await

```
chan in1(int), in2(int), out(int);

process Merge {
  int v1, v2;
  receive in1(v1);          # read the first two
  receive in2(v2);          # input values

  while (v1 != EOS and v2 != EOS) {
    if (v1 <= v2) { send out(v1); receive in1(v1); }
    else          { send out(v2); receive in2(v2); }
  }

  while (v1 != EOS) { send out(v1); receive in1(v1); }
  while (v2 != EOS) { send out(v2); receive in2(v2); }
  send out(EOS);
}
```

Sorting network

To scale, we can now build a network that sorts n numbers, using a collection of **Merge** processes with tables of shared input and output channels.



Call-Backs to a channel

How to communicate a result back via channels?
e.g., Assume a process that adds two numbers it receives via a channel.

Call-Backs to a channel

How to communicate a result back via channels?

e.g., Assume a process that adds two numbers it receives via a channel.

Bi-directional channel

Await

```
chan c(int);
process P {  int a, b;  receive c(a); receive c(b); send c(a+b); }
```

Requires same channel type for input and result.

Call-Backs to a channel

How to communicate a result back via channels?

e.g., Assume a process that adds two numbers it receives via a channel.

Answer channel per sender

Await

```
chan c(int), chan d[n](int);
process P {  int a, b;  int id;
    receive c(a); receive c(b); receive c(id); send d[id](a+b); }
```

Requires pre-sharing of channels, rather static.

Call-Backs to a channel

How to communicate a result back via channels?

e.g., Assume a process that adds two numbers it receives via a channel.

Call-back channel

Await

```
chan c(...);
process P {
    int a, b;
    chan res(int);
    receive c(a); receive c(b); receive c(res);
    send res(a+b);
}
```

Requires (a) sending channels over channels and (b) more complex type for c.

Message Passing

Client-server applications using messages

Roles

- Server process: repeatedly handling requests from clients
- Client processes: send requests to server, retrieve results later

Await

```
chan request(int, T1); # client ID, arguments of the operation
chan reply[n](T2); # result of the operation
```

Await

```
process Client[i = 1 to n]{
  ...
  send request(i, args);
  receive reply[i](var);
  ...
}
```

Await

```
process Server{
  while(true){ int id; ...
    receive request(id, args);
    ... # code of the operation
    send reply[id](result);
  } }
```

Monitor implemented using message passing

Monitors are very useful in a shared-memory setting, can we implement it in a channel-based concurrency model?

Classical monitor

- Controlled access to shared resource
- Global variables safeguard the resource state
- Access to a resource via procedures
- Procedures are executed under mutual exclusion
- Condition variables for synchronization

Active Monitors

- One server process that actively runs a loop listens on a channel for requests
- Procedure calls correspond to values send over request channel
- Resource and variables are local to server process

Allocator for multi–unit resources

Task

Multi–unit resource: a resource consisting of multiple units, which can be allocated separately, e.g., memory blocks, file blocks, etc.

- Client can request resources, use them, and return/free them
- All the access to resources is managed for safety by the allocator
- Unit usage itself is not managed

- Safety and efficient allocation is hard
- Several simplifications here, e.g., only one unit of resource requested at a time
- No focus on efficiency, resource is modeled as a set

Next Slides; Two versions

1. Allocator as (passive) monitor
2. Allocator as active monitor

Recap: semaphore monitor passing the condition

Await

```
monitor Semaphore       { # monitor invariant: s >= 0
  int s := 0;              # value of the semaphore
  cond pos;                # wait condition

  procedure Psem() {
    if (s=0) wait(pos);
    else     s := s - 1; }

  procedure Vsem() {
    if (empty(pos)) s := s + 1;
    else            signal(pos); }
}
```

Allocator as a monitor

Await

```
monitor Resource_Allocator {
  int avail := MAXUNITS;
  set units;
  cond free;         // signalled when process wants a unit

  procedure acquire(int &id) {
    if (avail = 0) wait(free);
    else           avail := avail-1;
    remove(units, id); } // exact management abstracted here

  procedure release(int id) {
    insert(units, id);
    if (empty(free)) avail := avail+1;
    else             signal(free); }
}
```

Allocator as a server process: code design process for monitors

1. Interface and internal variables

2. Control structure

3. Synchronization, scheduling, and mutex

Allocator as a server process: code design process for monitors

1. Interface and internal variables
    1.1 Two types of operations: `get` unit, `free` unit
    1.2 One request channel *encoded* in the arguments to a request.
2. Control structure
3. Synchronization, scheduling, and mutex

Allocator as a server process: code design process for monitors

1. Interface and internal variables
   1.1 Two types of operations: `get` unit, `free` unit
   1.2 One request channel *encoded* in the arguments to a request.
2. Control structure
   2.1 First check the kind of requested operation,
   2.2 Then, perform resource management for that operation
3. Synchronization, scheduling, and mutex

Allocator as a server process: code design process for monitors

1. Interface and internal variables
   1.1 Two types of operations: `get` unit, `free` unit
   1.2 One request channel *encoded* in the arguments to a request.
2. Control structure
   2.1 First check the kind of requested operation,
   2.2 Then, perform resource management for that operation
3. Synchronization, scheduling, and mutex
   3.1 Cannot wait (ie. `wait(free)`) when no unit is free.
   3.2 Must save the request and return to it later
   $\Rightarrow$ queue of pending requests (**queue**; **insert**, **remove**).
   3.3 Upon request: synchronous/blocking call $\Rightarrow$ “ack”-message back
   3.4 No internal parallelism due to mutex

Channel declarations

Await

```
type op_kind = enum(ACQUIRE, RELEASE);
chan request(int clientID, op_kind kind, int unitID);
chan reply[n](int unitID);

process Client[i = 0 to n-1] {
  int unitID;
  send request(i, ACQUIRE, unitID); // make request
  receive reply[i](unitID);         // works as ''if synchronous''
  ...                               // use resource unitID
  send request(i, RELEASE, unitID); // free resource
  ...
}
```

Note the problems with type-uniform channels: `ACQUIRE` request does not use he last parameter, `RELEASE` does not use the first one.

Await

```
process Resource_Allocator {
  int avail := MAXUNITS;
  set units := ...                    // initial value
  queue pending;                      // initially empty
  int clientID, unitID; op_kind kind; ...
  while (true) {
    receive request(clientID, kind, unitID);
    if (kind = ACQUIRE) {
      if (avail = 0) insert(pending, clientID); // save request
      else { //  perform request now
          avail:= avail-1;
          remove(units, unitID);
          send reply[clientID](unitID); } }
    else {                            // kind = RELEASE
      if empty(pending) avail := avail+1; insert(units, unitID);
      else {                          // allocates to waiting client
        remove(pending, clientID);
        send reply[clientID](unitID); } } } }
```

Duality: monitors, message passing

monitor-based programs	message-based programs
monitor variables	local server variables
process-IDs	`request` channel, operation types
procedure call	`send request()`, `receive reply[i]()`
go into a monitor	`receive request()`
procedure `return`	`send reply[i]()`
`wait` statement	save pending requests in a queue
`signal` statement	get and process pending request (`reply`)
procedure body	branches in branching over op. type

Synchronous message passing

Synchronous Channels

- Asynchronous channels pass messages, but do not synchronize two processes
- Next: Synchronous channels
- Natural connection to barriers

Primitives

```
synch_send c(expr1,...,exprN);
```

- Sender waits until message is received via the channel,
- Sender and receiver synchronize by the sending and receiving of message
- Same receiving primitive

Synchronous message passing: discussion

Advantages

- Gives maximum *size* of channel (for fixed number of processes), as sender synchronizes with receiver
    - Receiver has at most 1 pending message per channel per sender
    - Each sender has at most 1 unsent message

Disadvantages

- Reduced parallelism: when 2 processes communicate, 1 is always blocked
- Higher risk of *deadlock*

Example: blocking with synchronous message passing

Await

```
chan values(int);

process Producer {
 int data[n];
 for (i = 0 to n-1) {
   ... //computation
   synch_send values(data[i]); } }

process Consumer {
 int results[n];
 for (i = 0 to n-1) {
  receive values(results[i]);
  ... //computation
  } }
```

Example: blocking with synchronous message passing

Await

```
chan values(int);

process Producer {
 int data[n];
 for (i = 0 to n-1) {
   ... //computation
   synch_send values(data[i]); } }

process Consumer {
 int results[n];
 for (i = 0 to n-1) {
  receive values(results[i]);
  ... //computation
  } }
```

- Assume both producer and consumer vary in time complexity.
- Communication using `synch_send/receive` will block.
- With *asynchronous* message passing, the waiting is reduced.

Example:

Await

```
chan in1(int), in2(int);

process P1 {
  int v1 = 1, v2;
  synch_send in2(v1);
  receive in1(v2);}

process P2 {
  int v1, v2 = 2;
  synch_send in1(v2);
  receive in2(v1);}
```

Example: deadlock using synchronous message passing

Await

```
chan in1(int), in2(int);

process P1 {
  int v1 = 1, v2;
  synch_send in2(v1);
  receive in1(v2);}

process P2 {
  int v1, v2 = 2;
  synch_send in1(v2);
  receive in2(v1);}
```

- `P1` and `P2` both block on `synch_send` – program *deadlocks*
- One process must be modified to do `receive` first ⇒ asymmetric solution.
- With asynchronous channels, all goes well

Encoding

- Despite all, many implementations (e.g., Go) and theories (e.g., π-calculus have *synchronous channels*
- Main reason: It is easier to encode asynchronous message passing with synchronous channels than vice versa
- Requires way to spawn new thread/process

Await

```
chan v(int);

process Send{
  spawn { synch_send v(1); } //spawns new thread and continues
}
process Receive {
  int res
  receive v(res);
}
```

Summary

Today's lecture

- Shared memory vs. distributed memory
- Synchronous and asynchronous message passing, the high level picture
- *Asynchronous message passing*: channels, messages, primitives
- Example: filters and sorting networks
- Comparison of message passing and monitors
- Basics *synchronous message passing*

Next lectures in this module

- Actors with asynchronous communication / Await primitive
- Concurrency in Go