

## Homework 5: Message Passing

See Webcourses and the syllabus for due dates.

In this homework you will learn about the message passing model and basic techniques of programming in that model. The programming techniques include using port objects to create agents (state machines) [Concepts] [UseModels]. A few problems also make comparisons with the other models we have studied, and also with message passing features in other languages [EvaluateModels] [MapToLanguages].

Answers to English questions should be in your own words; don't just quote text from the textbook.

Your code should be written in the message passing model, so unless we specify otherwise, you must *not* use cells and assignment in your Oz solutions. Furthermore, note that the message passing model does *not* include the primitive `IsDet` or the library function `IsFree`; thus you are also prohibited from using either of these functions in your solutions. Although you can simulate cells using the message passing model (see problem 5), you should avoid using this simulation directly, instead use a port object's state directly. (You can also store state in the message queue of a port object.) Using the model as it is intended will make it clear what the state of each port object is.

You should use helping functions whenever you find that useful. Unless we specifically say how you are to solve a problem, feel free to use any non-mutating functions from the Oz library (base environment), especially functions like `Map` and `FoldR`.

For all Oz programming tasks, you must run your code using the Mozart/Oz system. For programming problems for which we provide tests, you can find them all in a zip file, which you can download from problem 1's assignment on Webcourses. If the tests don't pass, please try to say why they don't pass, as this enhances communication and makes commenting on the code easier and more specific to your problem.

Turn in (on Webcourses) your code and also turn in the output of your testing for all exercises that require code.

Please upload code as text files with the name given in the problem or testing file and with the suffix `.oz`. Please use the name of the main function as the name of the file. Please either paste into the webcourses answer PCell (preferred) or upload test output and English answers; If you choose to upload test output or English answers as separate files, use plain text files with suffix `.txt` (or PDF files with suffix `.pdf`). If you have a mix of code and English answers, you can put the English answers in the webcourses answer PCell (preferred) or use a text file with a `.oz` file suffix, and put comments in the file for the English parts. (In any case, don't put any spaces in your file names!)

Your code should compile with Oz, if it doesn't you probably should keep working on it. If you don't have time, at least tell us that you didn't get it to compile.

Don't hesitate to contact the staff if you are stuck at some point.

Read Chapter 5 of the textbook [VH04]. (See the syllabus for optional readings.)

### Reading Problems

The problems in this section are intended to get you to read the textbook, ideally in advance of class meetings.

Read chapter 5, through section 5.1 of the textbook [VH04] and answer the following questions.

1. [Concepts] [EvaluateModels]

Ports in the message passing model allow a thread to receive messages from many other threads, without the need for a deterministic or planned order for receiving messages and without forcing the other threads to synchronize.

- (a) (3 points) Briefly describe what capabilities described in the previous sentence are not possible in the declarative concurrent model (of chapter 4).
- (b) (3 points) What kinds of systems can be programmed in the message passing model that could not be programmed in the declarative concurrent model?

Read chapter 5, through section 5.2 of the textbook [VH04] and answer the following questions. For examples of uses of `NewPortObject`, see the `code examples` page.

2. [Concepts] [UseModels]

- (a) (5 points) By default, does a server created by using `NewPortObject` process messages concurrently, or one at a time?
- (b) (5 points) For what kind of problems must you use `NewPortObject` instead of `NewPortObject2`?

Read chapter 5, through section 5.3 of the textbook [VH04] and answer the following questions.

3. (5 points) [Concepts]

In the message passing model, how can an agent make two requests (e.g., to different servers) without waiting for the first request to finish?

## Regular Problems

### Message Passing Semantics and Expressiveness

For the problems in this subsection, see especially sections 5.1 and 5.2 of the textbook [VH04].

#### 4. (10 points) [UseModels]

Using Oz's message passing model, write a function `NewCounter` that takes no arguments and returns a port object. The returned port object should store an integer value in its state and can respond to the messages `inc` and `value(Var)`. Initially the value stored in the port object is 0. The message `inc` increments this value (adds 1 to it). The `value(Var)` message binds `Var` to the current value in the port object. Figure 1 contains some examples.

You must use `NewPortObject` in your solution (see the textbook, and the `NewPortObject.oz` file supplied with the test cases for this homework).

```
% $Id: NewCounterTest.oz,v 1.1 2010/04/14 04:19:49 leavens Exp leavens $
\insert 'NewCounter.oz'
\insert 'TestingNoStop.oz'
declare
{StartTesting 'Counter'}
MyCounter = {NewCounter}
{Test local R in {Send MyCounter value(R)} R end '==' 0}
{Send MyCounter inc}
{Test {Send MyCounter value($)} '==' 1}
{Send MyCounter inc}
{Test {Send MyCounter value($)} '==' 2}
{Send MyCounter inc}
{Send MyCounter inc}
{Test {Send MyCounter value($)} '==' 4}

MyCounter2 = {NewCounter}
{Test {Send MyCounter2 value($)} '==' 0}
{Send MyCounter2 inc}
{Test {Send MyCounter2 value($)} '==' 1}
{Send MyCounter2 inc}
{Test {Send MyCounter2 value($)} '==' 2}
for I in 1..12 do {Send MyCounter2 inc} end
{Test {Send MyCounter2 value($)} '==' 14}
{StartTesting done}
```

Figure 1: Testing code for Problem 4.

#### 5. (30 points) [Concepts] [UseModels]

Using Oz's message passing model, implement a data abstraction `<PCell>`, by writing the following functions and procedures.

```
NewPCell: <fun {$ <Value>}: <PCell>>
PCellSwap: <proc {$ <PCell> <Value> <Value>}>
PCellSet: <proc {$ <PCell> <Value>}>
PCellGet: <fun {$ <PCell>}: <Value>>
```

A PCell is like a Cell, in that it holds a value (of any type). The function call `{NewPCell X}` returns a new PCell containing the value X. The procedure call `{PCellSwap PC Old New}` atomically binds Old to the value in PCell PC and makes New be the new value contained in PCell PC. The procedure call `{PCellSet PC V}` makes the value V be the new value of PCell PC. The function call `{PCellGet PC}` returns the value contained in PCell PC.

Note that PCellSwap and PCellSet are **procs**, not **fun**s. If you make them **fun**s instead, your code will not work with the tests!

You must use the NewPortObject function, given in the book and supplied with the test cases for this homework, in your solution. (Hint: represent a PCell with a port object, have NewPCell return a port, and have the other functions send messages to the port. The state of the port object will be the PCell's value.)

You are *not* allowed to use cells in your solution!

Your code should pass the tests shown in Figure 2 on the following page.

6. (20 points) [Concepts] [UseModels]

Using Cells, but without using the message passing primitives NewPort and Send, define in Oz an ADT PortAsCell, which acts like the built-in port type, but is represented as a Cell. (For more about the imperative model and cells, look back at Section 1.12 of the textbook or forward to chapter 6.) The PortAsCell ADT has two operations:

```
MyNewPort: <fun {$ <Stream>}: <PortAsCell>>
MySend: <proc {$ <PortAsCell> <Value>}>,
```

which are intended to act like NewPort and Send. That is, the function MyNewPort takes an undetermined store variable, and returns a <PortAsCell>, which is a Cell that we want to act like a Port. The procedure MySend takes such a PortAsCell and a Value and adds the Value to the corresponding stream. In other words, the idea behind the ADT <PortAsCell> is that it should act like the built-in Port ADT of Oz, but be represented using Cells.

For this problem, don't worry about catching or prohibiting improper uses of the stream argument to MyNewPort (see Problem 14 on page 13). Also for the moment, don't worry about potential race conditions when multiple threads are used.

Hint: look at the semantics for NewPort and Send in section 5.1 of the textbook, which shows how these work in terms of the mutable memory. Mutable memory is like a collection of cells. Think of the port name as being represented by the cell's identity. The cell holds the undetermined store variable that is the end of the list. Note how the semantics of Send manipulates the mutable memory and works with new undetermined store variables to extend the list and keep track of the new end of the list.

Your code should pass the tests shown in Figure 3 on page 6.

You are *not* allowed to use Send, NewPort, or functions that call them (such as NewPortObject) in your solution, and you must use Cells in your solution.

7. [Concepts] [EvaluateModels]

This problem concerns the expressive power of the message passing model in comparison to the imperative model.

- (5 points) Can the PCell ADT of Problem 5 on the previous page do everything that a Cell can do in Oz? Briefly explain.
- (5 points) Can the PortAsCell ADT of Problem 6 do everything that a Port can do in a sequential Oz program? Briefly explain.

```

% $Id: PCellTest.oz,v 1.2 2009/04/04 21:53:56 leavens Exp leavens $
\insert 'PCell.oz'
\insert 'TestingNoStop.oz'
declare PC1 PC2 V1old V2old
{StartTesting 'PCell operations'}
PC1 = {NewPCell 1}
PC2 = {NewPCell 2}
{PCellSwap PC1 V1old 7}
{PCellSwap PC2 V2old 99}
{Test V1old '==' 1}
{Test V2old '==' 2}
declare V1x V2x
{PCellSwap PC1 V1x 88}
{PCellSwap PC2 V2x 333}
{Test V2x '==' 99}
{Test V1x '==' 7}
declare
EE = {PCellGet PC1}
{Test EE '==' 88}
TT0 = {PCellGet PC2}
{Test TT0 '==' 333}
TT1 = {PCellGet PC2}
{Test TT1 '==' 333}
EE2 = {PCellGet PC1}
{Test EE2 '==' 88}
{PCellSet PC1 4}
Four = {PCellGet PC1}
{Test Four '==' 4}
TT = {PCellGet PC2}
{Test TT '==' 333}
{PCellSet PC1 asymbolliteral}
ASL = {PCellGet PC1}
{Test ASL '==' asymbolliteral}
declare
X=1 Y=2 Z=3
PC={NewPCell Z}
{StartTesting 'Some equations'}
{Test {PCellGet {NewPCell X}} '==' X}
{PCellSet PC Y}
End = {PCellGet PC}
{Test End '==' Y}
% Waits make the done message come out after all the others.
{Wait TT0} {Wait TT1} {Wait ASL} {Wait EE} {Wait EE2} {Wait Four}
{Wait TT} {Wait End}
{StartTesting done}

```

Figure 2: Testing code for Problem 5 on page 3.

```

% $Id: PortAsCellTest.oz,v 1.2 2009/04/04 21:53:56 leavens Exp leavens $
\insert 'PortAsCell.oz'
\insert 'TestingNoStop.oz'

{StartTesting 'MyNewPort'}
% Simulating basic semantics of NewPort and Send
declare Strm Port in
Port = {MyNewPort Strm}
{StartTesting 'MySend'}
{MySend Port 3}
{MySend Port 4}
% Must use List.take, otherwise Test suspends...
{Test {List.take Strm 2} '==' [3 4]}
{MySend Port 5}
{MySend Port 6}
{Test {List.take Strm 4} '==' [3 4 5 6]}

{StartTesting 'MyNewPort second part'}
declare S2 P2 U1 U2 in
P2 = {MyNewPort S2}
{StartTesting 'MySend second part'}
{MySend P2 7}
{MySend P2 unit}
{MySend P2 true}
{MySend P2 U1}
{MySend P2 hmmm(x:U2)}
U1 = 4020
{Test {List.take S2 5} '==' [7 unit true 4020 hmmm(x:U2)]}
{Test {List.take Strm 4} '==' [3 4 5 6]}
{StartTesting done}

```

Figure 3: Testing code for Problem 6 on page 4.

## Message Passing Programming

For additional examples of message passing programming, see also the [code examples page](#).

### 8. (10 points) [UseModels]

Using Oz's message passing model, write a function `NewAccumulator` that takes one argument and returns a port object that accumulates the results of `apply` messages (see below), starting with the argument as the accumulator's initial value. The returned port object responds to the following messages:

- `apply(Fun)`, which applies the one-argument function `Fun` to the accumulator's value, and makes the accumulator remember the result as its new accumulator value, and
- `fetch(X)`, where `X` is an undetermined dataflow variable.

The result of `{NewAccumulator Init}` is a port object that remembers `Init` as its accumulator value.

When the port object receives the `apply(Fun)` message, it applies `Fun` to the accumulator's value, and uses the result of that call as its new accumulator value.

When the port object receives the `fetch(X)` message, where `X` is an undetermined dataflow variable, it unifies `X` with the current accumulator value, and leaves the accumulator value unchanged.

Figure 4 gives some tests.

```
% $Id: NewAccumulatorTest.oz,v 1.1 2010/04/15 02:56:51 leavens Exp leavens $
\insert 'NewAccumulator.oz'
\insert 'TestingNoStop.oz'
declare
{StartTesting 'NewAccumulator'}
MyAcc = {NewAccumulator 7}
{Test {Send MyAcc fetch($)} '==' 7}
{Send MyAcc apply(fun {$ Val} Val+100 end)}
{Test {Send MyAcc fetch($)} '==' 107}
{Send MyAcc apply(fun {$ Val} Val+1 end)}
{Test {Send MyAcc fetch($)} '==' 108}
{Send MyAcc apply(fun {$ Val} 2*Val+1000 end)}
{Test {Send MyAcc fetch($)} '==' 1216}
{Send MyAcc apply(fun {$ _} 1 end)}
{Test {Send MyAcc fetch($)} '==' 1}
A2 = {NewAccumulator 3}
{Test {Send A2 fetch($)} '==' 3}
{Send A2 apply(fun {$ Val} Val+4017 end)}
{Test {Send A2 fetch($)} '==' 4020}
{Test {Send MyAcc fetch($)} '==' 1}
{Send A2 apply(fun {$ Val} val_is(Val) end)}
{Test {Send A2 fetch($)} '==' val_is(4020)}
{Send A2 apply(fun {$ val_is(Val)} val_is(Val div 10) end)}
{Test {Send A2 fetch($)} '==' val_is(402)}
{Send A2 apply(fun {$ val_is(Val)} Val - 360 end)}
{Test {Send A2 fetch($)} '==' 42}
{StartTesting done}
```

Figure 4: Tests for problem Problem 8.

## 9. (20 points) [UseModels]

Using Oz's message passing model, write a function `NewFutureServer` that takes no arguments and returns a port object that acts as a "future server". A future server remembers a list of requests for the value of a computation, or a computed result, which is the value of the last computation it was called on to perform.

The returned port object understands the following messages:

- The `request(X)` message includes an undetermined dataflow variable,  $X$ ; if the server already has a computed result, then  $X$  is unified with the result. Otherwise if the server does not already have a computed result, then it remembers this request, in particular it remembers  $X$ , and when the server eventually has a computed result, it unifies  $X$  with that result.
- The `compute(F)` message includes a function `F` that takes no arguments; this function is run and its result defines the "computed result" that the server remembers. The computed result is unified with all dataflow variables from previous unfulfilled requests received by the server.

Note that when the future server already has a computed result, if it receives a `compute(F)` message, then it uses the result of `{F}` as the new computed result, which is used to answer further requests.

Hint: you can store undetermined dataflow variables in a list or other data structure, but be very careful not to try to pattern match or perform other computations that would need their values. You might try using different kinds of state records to remember the necessary information in the port object's state.

Figure 5 contains various tests.

```
% $Id: NewFutureServerTest.oz,v 1.1 2010/04/15 02:56:51 leavens Exp leavens $
\insert 'NewFutureServer.oz'
\insert 'TestingNoStop.oz'
{StartTesting 'NewFutureServer'}
declare
FS = {NewFutureServer}
local R1 R2 R3 R4 in
  {StartTesting 'initial requests'}
  {Send FS request(R1)}
  {Send FS request(R2)}
  {Send FS request(R3)}
  {Delay 1000}
  {Send FS compute(fun {$} {Pow 3 24} end)}
  {Wait R1}
  {Test R1 '==' R2}
  {Test R2 '==' 282429536481}
  {Send FS request(R4)}
  local R5 in
    {Send FS compute(fun {$} {Pow 3 4} end)}
    {Send FS request(R5)}
    {Test R5 '==' 81}
  end
end
{StartTesting done}
```

Figure 5: Testing for Problem 9.



## 10. (20 points) [UseModels]

Using Oz's message passing model, write a function `NewEBay` that takes no arguments and returns a port object that acts as an electronic auction house, like EBay.

This port object understands several messages.

The `bid(Amt Info DidIWin)` message places a bid on the item, where `Amt` is a non-negative integer (the number of dollars bid), `Info` is some information about the bidder (e.g., their name), and `DidIWin` is an undetermined store variable.

The `finish` message ends the auction and does all notification of the bidders. When the `finish` message is received, the `DidIWin` variable in the first bid message received whose `Amt` was the largest is bound to `true`, and all other `DidIWin` variables in other bid messages are bound to `false`. (Note that there may be no bids. In case of a tie, the first bid message received by the port with the highest amount wins. If any bid message is received after the `finish` message, it does not win. You can assume that only one `finish` message is ever sent to the port object.)

The `whoWon(Winner)` message will only be sent after the `finish` message. This message contains an undetermined dataflow variable, `Winner`, which is unified with the `Info` from the winning bid message (if any), or the atom `none` if there were no bids received by the port object.

Note that, to prevent bidders from gaining information before the auction is over, none of the `DidIWin` variables sent in the bid messages may be determined by before the port object receives the `finish` message. Thus the port object will have to remember at least the `DidIWin` variables from all the bids until the `finish` message is received.

You should use `NewPortObject` in your solution (see the textbook, and the `NewPortObject.oz` file supplied with the test cases for this homework).

Hint: you may want to use helping functions or procedures.

Figure 6 on the next page contains some examples.

## 11. (20 points) [UseModels]

Using Oz's message passing model, write a function `NewResourceArbiter` that takes no arguments and returns a port object that tracks the status of a some resource, such as a printer or access to a critical section of code. (The exact resource is not important for this problem).

The returned port object responds to the following messages:

- `query(X)`, where `X` is an undetermined dataflow variable,
- `reserve(X)`, where `X` is an undetermined dataflow variable, and
- `release`.

The port object should track a list of (undetermined) dataflow variables that have been sent to it in `reserve(X)` messages but not yet granted the resource, and it also should track the current status of the resource. The resource status can be either: "in use" or "not used." A newly created port object starts with the resource not used.

When the port object receives the `query(X)` message, it unifies `X` with an atom representing the current status of the resource, which will be either `inUse` (if the resource is being used) or `notUsed` (if the resource is not being used).

When the port object receives the `reserve(X)` message, the resource status becomes "in use" if it is not already, but what happens to `X` and the list of variables waiting depends on the resource's current status. If the resource is not currently in use, then it binds `X` to some atom, allowing the sender, which is a thread that should be waiting for `X` to be determined, to proceed. Otherwise, if the resource is in use, then the port object puts `X` at the end of the list of variables that represent processes waiting to use the resource.

When the port object receives the `release` message, what happens depends on the list of dataflow variables representing waiting threads. If that list is empty, then the resource status changes to being not used. If that list has some elements, then the first element in the list is unified with some atom (e.g., `unit`), which lets the thread

```

% $Id: NewEBayTest.oz,v 1.2 2010/04/15 20:36:03 leavens Exp $
\insert 'NewEBay.oz'
\insert 'TestingNoStop.oz'
declare
{StartTesting 'NewEBay'}
MyEBay = {NewEBay}
local Status1 Status2 Status3 Status4 in
  {Send MyEBay bid(8 palin Status1)}
  {Send MyEBay bid(17 mccain Status2)}
  {Send MyEBay bid(27 bush Status3)}
  {Send MyEBay bid(24 romney Status4)}
  % losing bids should not yet be determined
  {Test {IsDet Status1} '==' false}
  {Send MyEBay finish}
  {Test Status1 '==' false}
  {Test Status2 '==' false}
  {Test Status3 '==' true}
  {Test Status4 '==' false}
  {Test {Send MyEBay whoWon($)} '==' bush}
end
MyEBay2 = {NewEBay}
local Status1 Status2 Status3 Status4
  Status5 Status6 Status7
in
  {Send MyEBay2 bid(100 agent007 Status1)}
  {Send MyEBay2 bid(15 agent86 Status2)}
  {Send MyEBay2 bid(99 agent99 Status3)}
  {Send MyEBay2 bid(99 agent992 Status4)}
  {Send MyEBay2 bid(100 agent1002 Status5)}
  {Send MyEBay2 bid(100 agent1003 Status6)}
  {Send MyEBay2 bid(100 agent1004 Status7)}
  {Send MyEBay2 finish}
  {StartTesting 'first of the highest bids wins'}
  {Test Status1 '==' true}
  {Test Status2 '==' false}
  {Test Status3 '==' false}
  {Test Status4 '==' false}
  {Test Status5 '==' false}
  {Test Status6 '==' false}
  {Test Status7 '==' false}
  {Test {Send MyEBay2 whoWon($)} '==' agent007}
end
{StartTesting done}
{StartTesting 'finishing with no bids'}
MyEBay3 = {NewEBay}
{Send MyEBay3 finish}
{Test {Send MyEBay3 whoWon($)} '==' none}
{StartTesting 'bidding after an auction is over loses'}
{Test {Send MyEBay3 bid(50 mad_hatter $)} '==' false}
{Test {Send MyEBay bid(999 alice $)} '==' false}
{StartTesting done}

```

Figure 6: Testing for Problem 10 on the preceding page.

that is waiting on that dataflow variable proceed, and that variable is taken out of the list of waiting variables and the resource remains in use.

Figure 7 has some examples.

```

\insert 'NewResourceArbiter.oz'
\insert 'TestingNoStop.oz'
declare
proc {Acquire Port} % to avoid repeated testing code, for testing only
  local WaitVar in {Send Port reserve(WaitVar)} {Wait WaitVar} end
end

RA = {NewResourceArbiter}
{Test {Send RA query($)} '==' notUsed}
{Acquire RA}
{Test {Send RA query($)} '==' inUse}
{Send RA release}
{Test {Send RA query($)} '==' notUsed}

RA2 = {NewResourceArbiter}
local TestStrm P={NewPort TestStrm} in
  for ID in 1..2 do
    thread {Acquire RA2} {Send P ID} {Delay 5} {Send P ID} {Send RA2 release} end
  end
  local T4 = {List.take TestStrm 4} in
    {Test (T4 == [1 1 2 2] or else T4 == [2 2 1 1]) '==' true}
  end
end

```

Figure 7: Testing for Problem 11 on page 9.

## Comparisons Among Models

12. (10 points) [EvaluateModels]

Suppose you are asked to program a simulation of an agent-based auction system for someone doing research in economics. This system consists of several independent agents, each of which must communicate with a central auction server to evaluate merchandise, place bids, and make payments.

Among the programming models we studied this semester, what is the most restrictive (i.e., the least expressive or smallest) programming model that can practically be used program the overall structure of such a system? Briefly justify your answer.

13. (25 points) [EvaluateModels]

Update your table from homework 4 that lists all the different programming techniques, the characteristics of problems that are best solved with these techniques (i.e., when to use the techniques), and the name of at least one example of that technique. In this update, take into account comments from the staff from homework 4, and add entries for the new row on “message passing.”

programming technique	problem characteristics	example(s)
recursion (over grammars)		
higher-order functions		
stream programming		
lazy functions		
message passing		

## Extra Credit Problems

Please recall that the course grading policy is that extra credit problems do not directly affect your grade.

14. (20 points; extra credit) [Concepts] [UseModels]

Using read-only views (see Sections 3.7.5 and 13.1.14 of our textbook [VH04]), fix your solution to Problem 6 on page 4 so that your code has the same behavior for improper uses of the stream argument passed to `MyNewPort` as does Oz's built-in `NewPort` primitive.

You must show, by running your own tests, that your code has the required behavior for such (improper) uses. Testing is up to you and an important part of this exercise.

## Points

This homework's total points: 196. Total extra credit points: 20.

## References

[VH04] Peter Van Roy and Seif Haridi. *Concepts, Techniques, and Models of Computer Programming*. The MIT Press, Cambridge, Mass., 2004.