

6.823  
Computer System Architecture  
Lab 3

*Assigned Apr. 5, 2016*

Worth 5% of Course Grade

*Due Apr. 15, 2016*

---

<http://csg.csail.mit.edu/6.823/>

---

## Summary

Many modern multi-core computer systems support shared memory in hardware. In a shared memory system, each of the processor cores may read and write to a single shared address space. Cache coherence protocols, that manage the read and write permissions of data in various caches, are an important component in ensuring the correct operation of shared caches in a multi-core system.

Cache coherence protocols are challenging to design, in particular due to the multitude of races and corner cases. Verifying their correctness is a necessary, but very difficult aspect of the process. Sophisticated protocols have been developed and verified. However, this remains an active research area. In this assignment, we will design and verify a cache coherence protocol for a multi-core system.

To verify our coherence protocol, we will use Murphi, a formal verification tool. Murphi employs model checking to verify the correctness of the specified coherence protocol. Model checking is an automated technique, that given a finite-state model of a system and a set of formal properties, checks if the properties hold for all valid states of the system, in that model. More concretely, we will describe the finite-state machine corresponding to the coherence protocol in the Murphi description language, and enumerate a set of desired properties or invariants. The Murphi verifier will systematically enumerate the entire state space, and check that the specified invariants are not violated.

Murphi may be downloaded from the following web page: <http://formalverification.cs.utah.edu/software/murphi/>. However, we have provided you the necessary materials in the lab repository. As always, this lab is to be completed individually. You are encouraged to discuss lab concepts with fellow classmates.

## Setting up

To obtain the materials for lab 3, use the following commands, assuming that you start in your individual repository (cd \$USER) from the previous lab:

```
% svn export $LAB3ROOT
% svn add lab3handout
% svn commit -m "Lab 3 Initial Check-in"
```

In the lab3handout directory that just got created, you should find the Murphi source code and a protocol sub-folder, which contains some examples and the framework code to get you started. Type the following at the command prompt:

```
% cd lab3handout
```

First, we will build the Murphi compiler.

```
% cd Murphi/src
% make mu
% make install
% ln -s ../bin/mu.x86_64 ../bin/mu
```

Let us test a simple model. Run the following commands (assuming you start from lab3handout):

```
% cd protocol
% ../Murphi/bin/mu pingpong.m
```

pingpong.m contains a simple example written in the Murphi description language. Running it through the Murphi compiler should generate pingpong.C file.

```
% make pingpong
```

This builds the final verifier, which you can run as:

```
% ./pingpong -v
```

You can find other examples in the Murphi source code directory (.../Murphi/ex). The Murphi user manual is a useful resource to understand the language constructs. It is available within the Murphi source code directory (.../Murphi/doc/User.Manual).

## Lab Task

You will design and verify an invalidation-based cache coherence protocol. The protocol you develop will have a number of characteristics:

1. It uses an interconnect network that supports only point-to-point communication. All communication is done by sending and receiving messages. The interconnect network may reorder messages arbitrarily. It may delay messages, but it will always deliver messages eventually. Messages are never lost, corrupted or replicated. Message delivery cannot be assumed to be in the same order as they were sent, even for the same sender and receiver pair.
2. At the receiving side of the interconnect system, messages are delivered to a receive port. Once a message has been delivered to the receive port, it will block all subsequent messages to this port until the message is read. Consider this behavior equivalent to that of a mail-box with room for only one letter: you have to remove the letter from the mailbox before you can receive the next one. On the

- sending side, there is no such restriction: you can always send messages. The interconnect system has enough buffer space to queue messages.
3. For the purpose of this assignment, you may assume that there is no limit on the buffer space in the interconnect system. However, your protocol will be considered broken if there is a way to generate an infinite number of undelivered messages. Besides, you will not be able to verify your protocol in this case.
  4. You may assume that the interconnect network supports multiple lanes (i.e., virtual channels). For each lane, you have a separate set of send- and receive-ports for each unit. Traffic on one lane is independent of traffic on the other lanes. Messages will never switch lanes. Note that using fewer lanes is better.
  5. Each processor has a dedicated cache that is not shared with any other processor. All caches must be kept coherent by your cache coherence protocol. Processors may issue load and store operations only. Because this assignment only deals with cache coherence and not with consistency issues, you will be concerned with **only one storage location (address)**. However, you need to model cache conflicts. To do this, you need to model a third operation besides load and store: a cache write-back. Write-backs normally arise from a cache conflict if the old line is dirty. Write-back operations may occur at any time between any pair of load/store operations. If the cache is in a clean state, you may simply set it to be invalid or take the appropriate action according to your coherence protocol. Cache replacements of dirty lines must obviously write the line back to memory.
  6. You should assume that the coherence unit is equal to one word and that all loads and stores read or write the entire word.
  7. Besides processors with their caches, there is one memory unit in your system. The memory unit has a directory-based cache-consistency controller which ensures that only one processor can write to the memory block at a time (exclusive-ownership style protocol). The directory representation is unimportant for this assignment. You should assume that you have a full directory (bit vector) that can keep track of all sharers.
  8. The interconnect system can send messages from any unit to any other unit. It is OK if your protocol requires that a cache controller has to send a message to another cache controller.

For this assignment, your cache coherence protocol should not worry about consistency issues. Because of that, you may assume that the memory of this machine has only one word. Your protocol has to make sure that loads from up to three (3) processors always return the value of the most recent stores. In this context, this means that loads and stores issued by one processor are seen by that processor in program order.

The baseline protocol shall deliver data always in the state needed by the requesting processor. In other words, do not bother with speculating on supplying data in an exclusive state for a normal load. Exclusivity is always a consequence of a store. Therefore, in this case you only have 3 cache states: I = invalid, S = shared (read-only) and M = modified (exclusive and dirty). The memory unit could be regarded as a home-node without a processor, so it will never do anything on its own. For example, it will never issue an unsolicited recall-request.

**3-hop vs 4-hop protocol:**

A simple incarnation of the MSI protocol is the 4-hop protocol, where the directory is responsible for satisfying all data requests from the processors. Here, all requests for data are satisfied with at most 4 hops (one such 4-hop transaction is show in Figure 1).

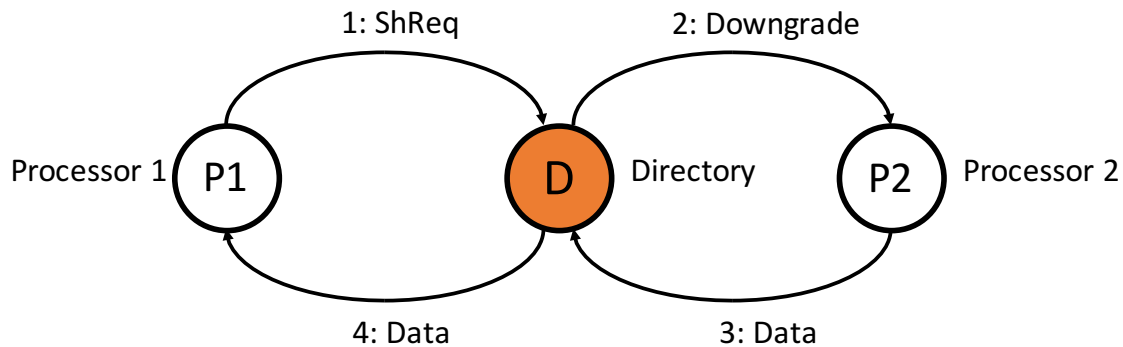


Figure 1: 4-hop transaction. Assume P2 originally has the address in M state. When P1 issues a ShReq, the directory D issues a downgrade request to P2, which writes back the data to the directory, which then forwards it to the requestor P1.

An optimization to reduce the latency of requests, is to allow P2 to respond to P1 directly with the data in the above scenario. The resulting transaction is shown in Figure 2. Allowing such forwarding of requests transforms the protocol to a 3-hop protocol.

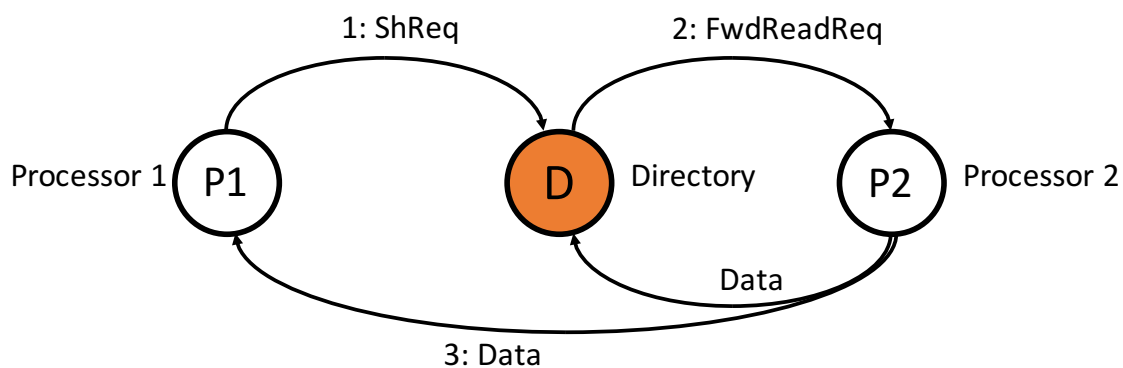


Figure 2: 3-hop transaction. P2 originally has the address in M state. When P1 issues a ShReq, the directory instead of issuing just a downgrade request, sends a FwdReadReq which contains the id of the requestor. P2 then sends the data to both the directory and P1, and also downgrades to the S state.

Your task is to write a 3-hop directory-based cache-coherence protocol based on the MSI protocol discussed in the lecture.

To help you get started we have provided you a framework code in `protocol/msi.m`. In addition, we have also provided a 4-hop Valid-Invalid (VI) protocol in `protocol/twostate.m` along with some guidelines on how you may proceed in developing your MSI protocol. While the 3-hop MSI protocol is slightly more complex, it may help to get started with the 4-hop MSI protocol, and then enable the forwarding optimization. We will grant partial credit for turning in a correct 4-hop MSI protocol.

Although your solution will not be graded on its performance in terms of wall clock time, you should note that your Teaching Assistants are impatient people. The TA solution runs in around 2 seconds on the class machines. For grading purposes, we will allow your tool to run for upto half an hour. After half an hour, we will kill your submission and assign a grade accordingly.

When you have completed the lab to your satisfaction, submit your changes to the svn repository. The deadline for submission is 23:59:59 EDT 15 April 2016. We'll grade whatever code you have checked in by the deadline. **No Late Submissions will be accepted!** Seriously.

## Lab Deliverables

Your final deliverable will be a 3-hop MSI protocol, specified and verified using the Murphi language. You should also turn in the following:

- (1) A description of your protocol.
- (2) State transition diagram(s) documenting the complete state machine for your protocol.
- (3) The output from Murphi showing the no errors were found, the number of states explored and running time.

When you have answered these questions to your satisfaction, put them in a file called `lab3questions.pdf` (or `lab3questions.doc`) in your `lab3handout` directory, then run the following to add them and commit them.

```
% svn add lab3questions.pdf
% svn commit -m "Lab 3 Questions Check-In"
```

As with the lab code, we'll grade whatever you have checked in by the deadline.

## Lab Grading

10%: Submission compiles

50%: Correct 4-hop MSI protocol

20%: Correct 3-hop MSI protocol

30%: Quality of lab response

## Advice on Mine Sweeping

There may be bugs in either our code or infrastructure. If you notice any `interesting' or `unexpected' behavior it could be a problem in the code or infrastructure that we provided. Report these bugs immediately to the TA, preferably in an email with the subject 6.823 Bug Report. This will help to ensure prompt fixing of any issues that may arise.

## Guides for the perplexed

<http://formalverification.cs.utah.edu/software/murphi/> - Murphi home page

<http://tig.csail.mit.edu/twiki/bin/view/TIG/UsingSubversionAtCSAIL> - an SVN tutorial

## Acknowledgements

Brian T. Gold, Carnegie Mellon University