Deriving Efficient Cache Coherence Protocols through Refinement

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Abstract

We address the problem of developing efficient cache coherence protocols for use in distributed systems implementing distributed shared memory (DSM) using message passing. A serious drawback of traditional approaches to this problem is that the users are required to state the desired coherence protocol at the level of asynchronous message interactions involving request, acknowledge, and negative acknowledge messages, and handle unexpected messages by introducing intermediate states. Proofs of correctness of protocols described in terms of low level asynchronous messages are very involved. Often the proofs hold only for specific configurations and buffer allocations. We propose a method in which the users state the desired protocol directly in terms of the desired high-level effect, namely synchronization and coordination, using the synchronous *rendezvous* construct. These descriptions are much easier to understand, much cheaper to verify than asynchronous protocols due to their small state spaces, and can be synthesized into efficient asynchronous protocols. In this paper, we present our protocol refinement procedure, prove its soundness, and provide examples of its efficiency. Our synthesis procedure applies to large classes of DSM protocols.

Keywords: Refinement, DSM protocols, Communication protocols.

1 Introduction

With the growing complexity of concurrent systems, automated procedures for developing protocols are growing in importance. In this paper, we are interested in protocol *refinement* procedures, which we define to be those that accept high-level specifications of protocols, and apply provably correct transformations on them to yield detailed implementations of protocols that run efficiently and have modest buffer resource requirements. Such procedures enable correctness proofs of protocols to be carried out with respect to high-level specifications, which can considerably reduce the proof effort. Once the refinement rules are shown to be sound, the detailed protocol implementations need not be verified. Also, if the refinement rules apply for a family of protocols, then case-specific proofs can be avoided.

In this paper, we address the problem of producing correct and efficient cache coherence protocols used in *distributed shared memory (DSM)* parallel computing systems. DSM systems have been widely researched in the academia as the next logical step in parallel processing [CKK96, LLG$^+$92, Kea94]. High-end workstation manufacturers also have introduced DSM systems lately [Cra93] thus providing added confirmation to the growing importance of DSM. A central problem in DSM systems is the design and implementation of distributed coherence protocols for shared cache lines using *message passing* [HP96]. The present-day approach to this problem consists of specifying the detailed interactions possible between computing nodes in terms of low-level requests, acknowledges, negative acknowledges, and dealing with "unexpected" messages. Difficulty of designing these protocols is compounded by the fact that verifying such low-level descriptions invites state explosion (when done using model-checking [EM95, DDHY92]) or tedious (when done using theorem-proving [PD96]) even for simple configurations. Often these low-level descriptions are model-checked for specific resource allocations (e.g. buffer sizes); it is often not known what would happen when these allocations are changed. Protocol refinement can help alleviate this situation considerably. Our contribution in this paper is a protocol refinement procedure which can be applied to derive a large class of DSM cache protocols.

Most of the problems in designing DSM cache coherence protocols are attributable to the apparent lack of atomicity in the implementation behaviors. Although some of the designers of these protocols may begin with a simple atomic-transaction view of the desired interactions, such a description is seldom written down. Instead, what gets written down as the "highest level" specification is a detailed protocol implementation which was arrived at through *ad hoc* reasoning of the situations that can arise. In this paper, we choose CSP [Hoa78] as our specification language to allow the designers to capture their initial atomic-transaction view. After model-checking this atomic-transaction protocol, it is automatically transformed into a detailed implementation. We refer to the atomic-transaction view as *rendezvous protocol* and the detailed implementation as *asynchronous protocol*. Rendezvous protocols are, typically, several orders of magnitude more efficient to model-check than their corresponding detailed implementations. In addition, as empirically observed in the context of a state of the art DSM machine project called the Avalanche [CKK96], our procedure can automatically produce protocol implementations that are comparable in *quality* to hand-designed asynchronous protocols, where quality is measured in terms of (1) the number of *request*, *acknowledge*, and *negative acknowledge* (nack) messages needed for carrying out the rendezvous specified in the given specification, and (2) the buffering requirements to guarantee a precisely defined and practically acceptable progress criterion.

2 Cache Coherency in Distributed Systems

In directory based cache coherent multiprocessor systems, the coherency of each line of shared memory is managed by a CPU node, called *home* node, or simply *home*[1]. All nodes that may access the shared line are called *remote* nodes. The home node is responsible for managing access to the shared line by all nodes without violating the coherency policy of the system. A simple protocol used in Avalanche, called migratory, is shown in Figures 2 and 3.

The remote nodes and home node engage in the following activity. Whenever a remote node R wishes to access the information in a shared line, it first checks if the data is available (with required access permissions) in its local cache. If so, R uses the data from the cache. If not, it sends a request for permissions to the home node of the line. The home node may then contact some other remote nodes to revoke their permissions in order to grant the required permissions to R. Finally, the home node grants the permissions (along with any required data) to R. As can be seen from this description, a remote node interacts only with the home node, while the home node interacts with all the remote nodes. This suggests that we can restrict the communication topology of interest to a *star* configuration, with the home node as the hub, without loosing any descriptive power. This decision helps synthesize more efficient asynchronous protocols, as we shall see later.

2.1 Complexity of Protocol Design

As already pointed out, most of the problems in the design of DSM protocols can be traced to lack of atomicity. For example, consider the following situation. A shared line is being read

[1] The home for different cache lines can be different. We will derive protocols focusing on one cache line, as is usually done.

by a number of remote nodes. One of these remote nodes, say R1, wishes to modify the data, hence sends a request to the home node for write permission. The home node then contacts all other remote nodes that are currently accessing the data to revoke their read permissions, and then grants the write permission to R1. Unfortunately, it is incorrect to *abstract* as an atomic step, the entire sequence of actions consisting of contacting all other remote nodes to revoke permissions and granting permissions to R1. This is because when the home node is in the process of revoking permissions, a different remote node, say R2, may wish to obtain read permissions. In this case, the request from R2 must be either nacked or buffered for later processing. Such handling of unexpected messages requires introducing intermediate states, called *transient* states, into the protocol, leading to the complexity of DSM protocols. On the other hand, as we will show in the rest of the paper, if the user is allowed to state the desired interactions using an atomic view, it is possible to *refine* such a description using a refinement procedure that introduces transient states appropriately to handle such unexpected messages. Making such refined protocols efficient through syntactic restrictions is discussed in Section 2.4.

2.2 Communication Model

We assume that the network that connects the nodes in the systems provides *reliable, point-to-point in-order delivery* of messages. This assumption is justified in many machines, e.g., DASH [LLG$^+$92], and Avalanche [CKK96]. We also assume that the network has infinite buffering, in the sense that the network can always accept new messages to be delivered. Without this assumption, the asynchronous protocol generated may deadlock. Unfortunately, this assumption is not satisfied in many networks. A solution to this problem that is orthogonal to the refinement process is given by Hennessy and Patterson [HP96]. They divide the messages into two categories: *request* and *acknowledge*. A *request* message may cause the recipient to generate more messages in order to complete the transactions, while an *acknowledge* message does not. The authors argue that if the network always accepts *acknowledge* messages (as opposed to all messages in the case of a network with infinite buffer), such deadlocks are broken. As we shall see in Section 3, asynchronous protocol has two *acknowledge* messages: ack and nack. Guaranteeing that the network always accepts these two *acknowledge* messages is beyond the scope of this paper.

2.3 Methodology

We use rendezvous communication primitives of CSP [Hoa78] to specify the home node and the remote nodes to simplify the the DSM protocol design. In particular, we use direct addressing scheme of CSP, where every input statement in process `Q` is of the form `P?msg(v)` or `P?msg`, where `P` is the identity of the process that sent the message, `msg` is an *enumerated constant* ("message type") and `v` is a variable (local variable of `Q`) which would be set to the contents of the message, and every output statement in `Q` is of the form `P!msg(e)` or `P!msg` where `e` is an expression involving constants and/or local variables of `Q`. When P and Q rendezvous by P executing `Q!m(e)` and Q executing `P?m(v)`, we say that P is an active process and Q is a passive process in the rendezvous.

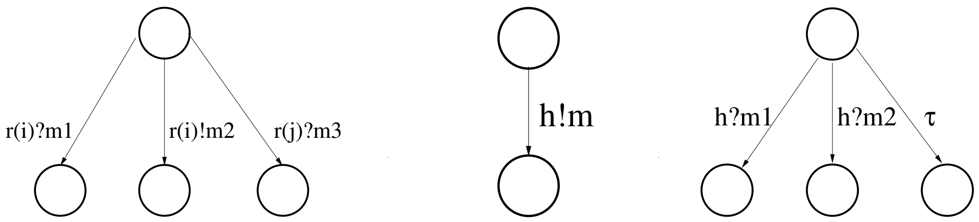
The rendezvous protocol written using this notation is verified using either a theorem prover or a model checker for desired properties, and then refined using the rules presented in Section 3 to obtain an *efficient* asynchronous protocol that can be implemented directly, for example in microcode.

2.4 Process Structure

We divide the states of processes in the rendezvous protocol into two classes: *internal* and *communication*. When a process is in an internal state, it cannot participate in rendezvous with any other process. However, we assume that such a process will eventually enter a communication state where rendezvous actions are offered (this assumption can be syntactically checked). The refinement process introduces *transient* states where all unexpected messages are handled.

We denote the i^{th} remote node by r_i and the home node by h. For simplicity, we assume that all the remote nodes follow the same protocol and that the only form of communication between processes (in both asynchronous and rendezvous protocols) is through messages, i.e., other forms of communication such as global variables are not available.

As discussed before, we restrict the communication topology to a star. Since the home node can communicate with all the remote nodes and behaves like a *server* of remote-node requests, it is natural to allow generalized input/output guards in the home node protocols (e.g., Figure 1(a)). In contrast, we restrict the remote nodes to contain only input non-determinism, i.e., a remote node can either specify that it wishes to be an active participant of a single rendezvous with the home node (e.g., Figure 1(b)) or it may specify that it is willing to be a passive participant of a rendezvous on a number of messages (e.g., Figure 1(c)). Also, as in Figure 1(c), we allow τ guards in the remote node to model autonomous decisions such as cache evictions. These decisions, empirically validated on a large number of real DSM protocols, help synthesize more efficient protocols. Finally, we assume that no fairness conditions are placed on the non-deterministic communication options available from a communication state, with the exception of the forward progress restriction imposed on



(a) Home node (b) Remote node (c) Remote node

Figure 1: Examples of communication states in the home node and remote nodes

the entire system (described below).

2.5 Forward Progress

Assuming that there are no τ loops in the home node and remote nodes, the refinement process guarantees that at least one of the refined remote nodes makes forward progress, if forward progress is possible in the rendezvous protocol. Notice that forward progress is guaranteed for some remote node, not for every remote node. This is because assuring forward progress for each remote node requires too much buffer space at the home node. If there are n remote nodes, to assure that every remote node makes progress, the home node needs a buffer that can hold n requests. This is both impractical and non-scalable as n in DSM machines can be as high as a few thousands. If we were to guarantee progress only for some remote node, a buffer that can hold 2 messages suffices, as shown in Section 3. Incidentally, assuring forward progress for each individual remote node corresponds to strong fairness, and assuring forward progress for at least one remote node corresponds to weak fairness [MP92].

3 The Refinement Procedures

We systematically refine the communication actions in h and r_i by inspecting the syntactic structure of the processes. The technique is to split each rendezvous into two halves: a request for the rendezvous and an acknowledgment (ack) or negative acknowledgment (nack) to indicate the success or failure of the rendezvous. At any given time, a refined process is

Row	State	Buffer contents	Action
C1	Communication (Active)	empty	(a) Request for rendezvous (b) goto transient state
C2	Communication (Active)	request	(a) delete the request (b) Request home for rendezvous (c) goto transient state
C3	Communication (Passive)	request	Ack/nack the request
T1	Transient	ack	Successful rendezvous
T2	Transient	nack	go back to the communication state
T3	Transient	request	Ignore the request

Table 1: The actions taken by the remote node when it enters a communication state or a transient state. After each action, the message in the buffer is removed.

in one of three states: *internal*, *communication*, and *transient*. Internal and communication states of the refined process are same as in the corresponding unrefined process in the rendezvous protocol. Transient states are introduced by the refinement process in the following manner. Whenever a process P has `Q!m(e)` as one of the guards in a communication state, P sends a request to Q and awaits in a transient state for an ack/nack or a request for rendezvous from Q. In the transient state, P behaves as follows:

R1. If P receives an ack from Q, the rendezvous is successful, and P changes its state appropriately.

R2. If P receives a nack from Q, the rendezvous has failed. P goes back to the communication state and tries the same rendezvous or a different rendezvous.

R3. If P receives a request from Q, the action taken depends on whether P is the home node or a remote node. If P is a remote node (and Q is then the home node), P simply ignores the message. (This is because, as discussed in the next sentence, P "knows" that Q will get its request that is tantamount to a nack of Q's own request.) If P is the home node, it goes back to the communication state as though it received a nack ("implicit nack"), and processes the Q's request in the communication state.

The rules R1-R3 govern how the remote node and home node are refined, as will now be detailed.

3.1 Refining the Remote Node

Every remote node has a buffer to store one message from the home node. When the remote node receives a request from the home node, the request would be held in the buffer. When a remote node is at a communication or transient state, its actions are shown in Table 1. The rows of the table are explained below.

C1 When the remote node is in a communication state, and it wishes to be an active participant of the rendezvous, and no request from home node is pending in the buffer, the remote node sends a request for rendezvous to home, goes to a transient state and awaits for an ack/nack or a request for rendezvous from home node.

C2 This row is similar to C1, except that there is a request from home is pending in the buffer. In this case also, the remote sends a request to home and goes to a transient state. In addition, the request in the buffer is deleted. As explained in R3, when the home receives the remote's request, it acts as though a nack is received (implicit nack) for the deleted request.

C3 When the remote node is in a communication state, and it is passive in the rendezvous, it waits for a request for rendezvous from home. If the request satisfies any guards of the communication state, it sends an ack to the home and changes state to reflect a successful rendezvous. If not, it sends a nack to home and continues to wait for a matching request. In both cases, the request is removed from the buffer.

T1, T2 If the remote node receives an ack, the rendezvous is successful, and the state of the process is appropriately changed to reflect the completion of the rendezvous. If the remote node receives a nack from the home, it is because the home node does not have sufficient buffers to hold the request. In this case, the remote node goes back to communication state and retransmits the request, and reenters the transient state.

T3 As explained in R3, if the remote node receives a request from home, it simply deletes the request from buffer, and continues to wait for an ack/nack from home.

3.2 Refining the Home Node

The home node has a buffer of capacity k messages ($k \geq 2$). All incoming messages are entered into the buffer when there is space, with the following exception. The last buffer location (called the *progress buffer*) is reserved for an incoming request for rendezvous that is known to complete a rendezvous in the current state of the home. If no such reservation

Row	State	Condition	Action
C1	Communication	buffer contains a request from r_i that satisfies a rendezvous	(a) an ack is sent to r_i (b) delete request from buffer
C2	Communication	(a) no request in the buffer satisfies any required rendezvous (b) home node can be active in a rendezvous with r_i on m_i (i.e. $r_i!m_i$ is a guard in this state) (c) no request from r_i is pending in buffer	(a) ack buffer is allocated (if not enough buffer space a nack may be generated) (b) a request for rendezvous is sent to r_i (c) goto transient state
T1	Transient	ack from r_i	rendezvous is completed
T2	Transient	nack from r_i	rendezvous failed. Go back to the communication state and send next request. If no more requests left, repeat starting with the first guard.
T3	Transient	(a) request from r_i (b) waiting for ack/nack from r_i	treat the request as a a nack plus a request
T4	Transient	(a) request from $r_j \neq r_i$ has arrived (b) waiting for ack/nack from r_i (c) buffer has > 2 free entries	enter the request into buffer
T5	Transient	(a) request from $r_j \neq r_i$ has arrived (b) waiting for ack/nack from r_i (c) buffer has 2 free entries (d) the request can satisfy a guard in the communication state	enter the request into progress buffer
T6	Transient	request from r_j has arrived (all cases not covered above)	nack the request

Table 2: Actions taken by the home node when it is in a communication state or transient state.

is made, a livelock can result. For example, consider the situation when the buffer is full and none of the requests in the buffer can enable a guard in the home node. Due to lack of buffer space, any new requests for rendezvous must be nacked, thus the home node can no longer make progress. In addition, when the home node is in a transient state expecting an ack/nack from r_i, an *additional* buffer need to be reserved so that a message (ack, nack, or request for rendezvous) from r_i can be held. We refer to this buffer as *ack buffer*.

When the home is in a communication or transient state, the actions taken are shown in Table 2. The rows of this table are explained below.

C1 When the home is in a communication state, and it can accept one or more requests pending in the buffer, the home finishes rendezvous by arbitrarily picking one of these messages.

C2 If no requests pending in the buffer can satisfy any guard of the communication state, and one of the guards of the communication state is $r_i!m_i$, home node sends a request for rendezvous to r_i, and enters a transient state. As described above, before sending the message, it also reserves an additional buffer location, ack buffer, so that forward progress can be assured. This step may require the home to generate a nack for one of the requests in the buffer in order to free the buffer location. Also note that condition (c) states that no request from r_i is pending in the buffer. The rationale behind this condition is that, if there is a request from r_i pending, then r_i is at a communication state with r_i being the active participant of the rendezvous. Due to the syntactic restrictions placed on the description of the remote nodes, r_i can't satisfy any requests for rendezvous in this communication state. Hence it is wasteful to send any request to r_i in this case.

T1 When the home is in transient state, if it receives an ack, the rendezvous is successful, and the state of the home is modified to reflect the completion of the rendezvous.

T2 When the home is in transient state, if it receives a nack the rendezvous failed. Hence the home goes back to the communication state. From the communication state, it checks if any new request in the buffer can satisfy any guard of the communication state. If so, an ack is generated corresponding to that request, and that rendezvous is completed. If not, the home tries the next output guard of the communication state. If there are no more output guards, it starts all over again with the first output guard. The reason for this is that, even though a previous attempt to rendezvous has failed, it may now succeed, because the remote node in question might have changed its state through a τ guard in its communication state.

T3 When the home is expecting an ack/nack from r_i, if it receives a request from r_i instead, it uses the implicit nack rule, R3. It first assumes that a nack is received, hence it goes to the communication state, where all the requests, including the request from r_i, are processed as in row T2.

T4 If the home receives a request from r_j, when it is expecting an ack/nack from a different remote r_i, and there is sufficient room in the buffer, the request is added to the buffer.

T5 When the home is in a transient state, and has only two buffer spaces, if it receives a message from r_j, it adds the request to buffer according to the buffer reservation scheme, i.e., the request is entered into the progress buffer iff the request can satisfy one of the guards of the communication state. If the request can't satisfy any guards, it would be handled by row T6.

T6 When a request for rendezvous from r_j is received, and there is insufficient buffer space (all cases not covered by T4 and T5), home sends a nack to r_j. r_j would retransmit the message.

3.3 Request/Reply Communication

The generic scheme outlined above replaces each rendezvous action with two messages: a request and an ack. In some cases, it is possible to avoid ack message. An example is when two messages, say `req` and `repl` are used in the following manner: `req` is sent from the remote node to home node for some service. The home node, after receiving the `req` message, performs some internal actions and/or communications with other remote nodes and sends a `repl` message to the remote node. In this case, it is possible to avoid exchanging ack for both `req` and `repl`. If statements `h!req(e)` and `h?repl(v)` always appear together as `h!req(e); h?repl(v)` in remote node, and r_i`!repl` always appears *after* r_i`?req` in the home node, then the acks can be dropped. This is because whenever the home node sends a `repl` message, the remote node is always ready to receive the message, hence the home node doesn't have to wait for an ack. In addition, a reception of `repl` by the remote node also acts as an ack for `req`. Of course, if the remote node receives a nack instead of `repl`, the remote node would retransmit the request for rendezvous.

This scheme can also be used when `req` is sent by the home node and the remote node responds with a `repl`. In this case, of course, after receiving `req`, the remote node performs local actions only (i.e., no rendezvous actions) and responds with a `repl`.

4 Correctness

We argue that the refinement is correct by analyzing the different scenarios that can arise during the execution of the asynchronous protocol. The argument is divided into two parts: (a) all rendezvous that happen in the asynchronous protocol are allowed by the rendezvous protocol, and (b) forward progress is assured for at least one remote node. Note that the forward progress is not assured for any given remote node due to buffer considerations (Section 2.5).

The rendezvous finished in the asynchronous protocol when the remote node executes rows C1, C3, or T1 of Table 1 and the home node executes rows C1 or T1 of Table 2. To see that all the rendezvous are in accordance with the rendezvous protocol, consider what happens when a remote node is the active participant in the rendezvous (the case when the home node is the active participant is similar). The remote node r_i sends out a request for rendezvous to the home h and starts waiting for an ack/nack. There are three cases to consider.

1. h does not have sufficient buffer space. In this case the request is nacked. In this case, no rendezvous has taken place.
2. h has sufficient buffer space, and it is in either an internal state or a transient state where it is expecting an ack/nack from a different remote node, r_j. In this case, the message is entered into the h's buffer. When h enters a communication state where it can accept the request, it sends an ack to r_i, completing the rendezvous. Clearly, this rendezvous is allowed by the rendezvous protocol. If h has to send a nack to r_i later to make some space in buffer by row C2, r_i would retransmit the request, in which case no rendezvous has taken place.
3. h has sent a request for rendezvous to r_i and is waiting for an ack/nack from r_i in a transient state. (This corresponds to R3 of page 7). In this case, r_i simply ignores the request from h. h knows that its request would be dropped. Hence it treats the request from r_i as a combination of nack for the request it already sent and a request for rendezvous. Thus, this case becomes exactly like one of the two cases above, and h generates an ack/nack accordingly; hence if an ack is generated it would be allowed by the rendezvous protocol.

As can be seen from this case analysis, an ack is generated only in case 2, and in this case the rendezvous is allowed by the rendezvous protocol.

A formal argument of correctness would involve demonstrating an abstraction function, abs, that maps a state in the asynchronous protocol to a state in the rendezvous protocol, and showing that for every sequence of states in the asynchronous protocol, there is an equivalent sequence of states in the rendezvous protocol. Of course, since the asynchronous protocol implements a rendezvous in multiple steps while the rendezvous protocol implements the same rendezvous in a single step, abs must allow stuttering steps. Let S_l be the set of states in the asynchronous protocol, $q \rightarrow_l q^{'}$ indicate a state transition from q to $q^{'}$ in the asynchronous protocol, and $q \rightarrow_h q^{'}$ indicate a state transition from q to $q^{'}$ in the rendezvous protocol.

$$\forall q_l \in S_l \; \forall q_l^{'} \in S_l \;\; : \;\; q_l \rightarrow_l q_l^{'} \Rightarrow abs(q_l) = abs(q_l^{'}) \; \vee \; abs(q_l) \rightarrow_h abs(q_l^{'}). \qquad (1)$$

Such an abstraction function can be designed as follows:

1. All requests for rendezvous in the medium and buffers are discarded. If a request for rendezvous from a process P is discarded, the state of P is modified from transient state back to the communication state, i.e., abs modifies the system as though the request was never sent.

2. If there is an ack towards a process P, the ack is discarded, and the state of P is modified to the state which P would attain after consuming the ack.

3. All nacks in the medium and buffers are also discarded. If a nack sent to P is discarded, the state of P is changed from transient state back to the communication state.

One can show that $\rightarrow_l$ defined by Tables 1 and 2, along with the above abs function satisfies Equation 1. Note that in the case of request/reply transformation, a `repl` message is treated as an ack.

To see that at least one of the remote nodes makes forward progress, we observe that when the home node h makes forward progress, one of the remote nodes also makes forward progress. Since we disallow any process to stay in internal states forever, from every internal state h eventually reaches a communication state from which it may go to a transient state. Note that because of the same restriction, when h sends a request to a remote node, the remote would eventually respond with an ack, nack, or a request for rendezvous. If any forward progress is possible in the rendezvous protocol, we show that h would eventually leave the communication or the transient state by the following case analysis.

1. h is in a communication state, and it completes a rendezvous by row C1 of Table 2. Clearly, progress is being made.

2. h is in a communication state, and conditions for row C1 and C2 of Table 2 are not enabled. h continues to wait for a request for rendezvous that would enable a guard in it. Since a buffer location is used as progress buffer, if progress is possible in the rendezvous protocol, at least one such request would be entered into the buffer, which enables C1.

3. h is in a communication state, row C2 of Table 2 is enabled. In this case, h sends a request for rendezvous, and goes to transient state. Cases below argue that it eventually makes progress.

4. h is in a transient state, and receives an ack. By row T1 of Table 2, the rendezvous is completed, hence progress is made.

5. h is in a transient state, and receives a nack (row T2 of Table 2) or an implicit nack (row T3 of Table 2). In response to the nack, the home goes back to the communication state. In this case, the progress argument is based on the requests for rendezvous that h has received while it was in the transient state, and the buffer reservation scheme. If one or more requests received enable a guard in the communication state, at least one such request is entered into the buffer by rows T4 or T5. Hence an ack is sent in response to one such request when h goes back to the communication state (row C1), thus making progress. If no such requests are received, h sends request for rendezvous corresponding to another output guard (row C2) and reenters the transient state. This process is repeated until h makes progress by taking actions in C1 or T1. If any progress is possible, eventually either T1 would be enabled, since h keeps trying all output guards repeatedly, or C1 would be enabled, since h repeatedly enters communication state repeatedly from T2 or T3, and checks for incoming requests for rendezvous. So, unless the rendezvous protocol is deadlocked, the asynchronous protocol makes progress.

5 Example Protocol

We take the rendezvous specification of migratory protocol of Avalanche and show how the protocol can be refined using the refinement rules described above. (The architectural team of Avalanche had previously developed the asynchronous migratory protocol without using the refinement rules described in this paper.) The protocol followed by the home node is shown in Figure 2, and the protocol followed by the remote nodes is shown in Figure 3. Initially the home node starts in state F (free) indicating that no remote node has access permissions to the line. When a remote node r_i needs to read/write the shared line, it sends a `req` message to the home node. The home node then sends a `gr` (grant) message to r_i along with data. In addition, the home node also records the identity of r_i in a variable `o` (owner) for later use. Then the home node goes to state E (exclusive). When the owner no longer needs the data, it may relinquish the line (`LR` message). As a result of receiving the `LR` message, the home node goes back to F. When the home node is in E, if it receives a `req` from another remote node, the home node revokes the permissions from the current owner and then grants the line to the new requester. To revoke the permissions, it either sends an `inv` (invalidate) message to the current owner `o` and waits for the new value of data (obtained through `ID` (invalid done) message), or waits for a `LR` message from `o`. After revoking the permissions from the current owner, a `gr` message is sent to the new requester, and the variable `o` is modified to reflect the new owner.

The remote node initially starts in state I (invalid). When the CPU tries to read or write

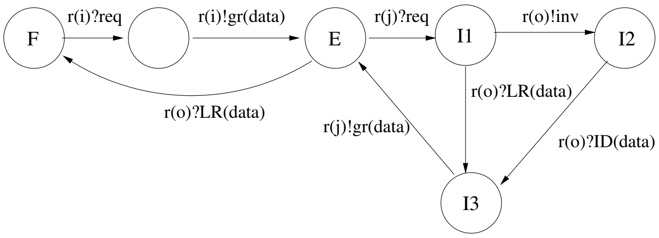


Figure 2: Home node of the migratory protocol

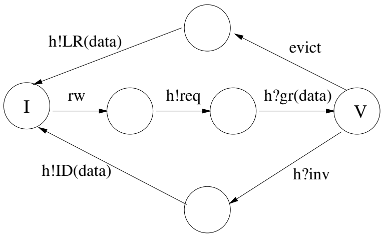


Figure 3: Remote node of the migratory protocol

(shown as `rw` in the figure), a `req` is sent to the home node for permissions. Once a `gr` message arrives, the remote node changes the state to V (valid) where the CPU can read or write a local copy of the line. When the line is evicted (for capacity reasons, for example), a `LR` is sent to the home node. Or, when another remote node attempts to access the line, the home node may send an `inv`. In response to `inv`, an `ID` (invalid done) is sent to the home node and the line reverts back to the state I.

To refine the migratory protocol, we note that the messages `req` and `gr` can be refined using the request/reply strategy. This is because the remote node after sending a `req` message immediately waits for a `gr` message from the home node. The home node, on the other hand, after receiving a `req` message, either sends a `gr` message (resulting in state change from F to E) or may have to contact a remote node and then send a `gr` message (resulting in a state change from E back to E, via E-I1-I3-E or E-I1-I2-I3-E). Similarly, the messages `inv` and `ID` can be refined using request/reply, except that in this case `inv` is sent by the home node, and the remote node responds with an `ID`. By following the request/reply strategy, a pair of consecutive rendezvous such as $r_i?\mathtt{req}$; $r_i!\mathtt{gr}$ or $r_i!\mathtt{inv}$; $r_i?\mathtt{ID}$ (data) takes only 2 messages as in Figures 4 and 5.

The refined home node is shown in Figure 4 and the refined remote node is shown in Fig-

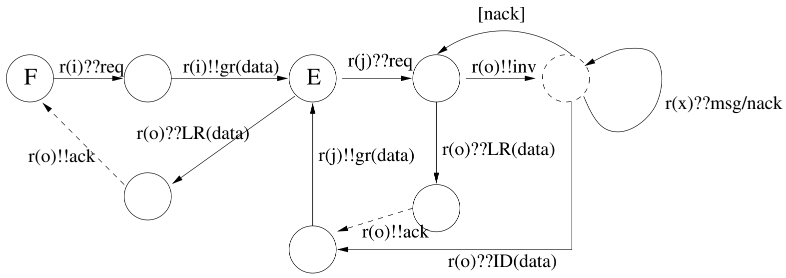


Figure 4: Refined home node of the Migratory protocol

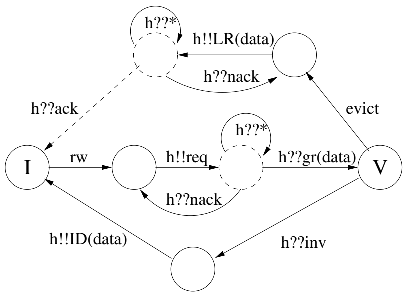


Figure 5: Refined remote node of the Migratory protocol

ure 5. In these figures, the operators "??" and "!!" are used instead of "?" and "!" to emphasize that the communication is asynchronous. In both these figures, transient states are shown as dotted circles (the dotted arrows are explained later). As discussed in Section 3.2, when the refined home node is in a transient state, if it receives a request from the process from which it is expecting an ack/nack, it would be treated as a combination of a nack and a request. To emphasize this, we write `[nack]` to imply that the home node has received the nack as either an explicit nack message or an implicit nack. Again, as discussed in Section 3.2, when the home node doesn't have sufficient number of empty buffers, it nacks the requests, irrespective of whether the node is in an internal, transient, or communication state. For the sake of clarity, we left out all such nacks other than the one on transient state (labeled `r(x)??msg/nack`).

As explained in Section 3.1, when the remote node is in a transient state, if it receives a message from the home node, the remote node ignores the message; no ack/nack is ever generated in response to this request. In Figure 5, we showed this as a self loop on the transient states, labeled `h??*`.

Protocol	N	Asynchronous protocol	Rendezvous protocol
Migratory	2	23163/2.84	54/0.1
	4	Unfinished	235/0.4
	8	Unfinished	965/0.5
Invalidate	2	193389/19.23	546/0.6
	4	Unfinished	18686/2.3
	6	Unfinished	228334/18.4

Table 3: Number of states visited and time taken in seconds for reachability analysis of the rendezvous and asynchronous versions of the migratory and invalidate protocols. All verifications were limited to 64MB of memory.

The asynchronous protocol designed by the Avalanche design team differs from the protocol shown in Figures 4 and 5 in that in their protocol the dotted lines are τ actions, i.e., no ack is exchanged after an `LR` message. We believe that the loss of efficiency due to the extra ack is small. We are currently in the process of quantifying the efficiency of the asynchronous protocol designed by hand and the asynchronous protocol obtained by the refinement procedure.

Efficiency

We verified the rendezvous and asynchronous versions of the migratory protocol above and invalidate, another DSM protocol used in Avalanche, using the SPIN [Hol91] model checker. The number of states visited by SPIN on these two protocols is shown in Figure 3. The complexity of verifying the hand designed migratory or invalidate is comparable to the verification of asynchronous protocol. As can be seen, verifying of the rendezvous protocol generates far fewer states and takes much less run time than verifying the asynchronous protocol. In fact, the rendezvous migratory protocol could be model checked for up to 64 nodes using 32MB of memory, while the asynchronous protocol can be model checked for only two nodes using 64MB of memory.

6 Buffer Requirements and Fairness

In Section 2.5, we mentioned that the refinement process preserves forward progress for at least one remote node, but doesn't guarantee forward progress for any *given* remote node.

This means that, it is possible that one of the nodes may starve. For example, a request for a rendezvous from a remote node might be continually nacked by the home node. This problem can be solved if the size of the buffer in the home node is n, where n is the number of the remote nodes. In this case, the home node *never* generates a nack. If the messages in the home node's buffer are processed in a fair manner, one can show that no remote node is starved.

However, this requires too much memory to be reserved for buffers. For example, in a multiprocessor with 64 nodes, if each node of the multiprocessor acts as home for 1024 lines (a modest number of lines), the node needs to reserve a total of 64K messages to be used as buffer space. Clearly, it is impractical to reserve such a large amount of space for buffer. Hence, it is impractical to guarantee forward progress per each remote node by *refinement alone*. However, it is usually not difficult to ensure the forward progress when other properties of modern CPUs are considered. A modern CPU can have a small number, say 8, of transactions outstanding. If the home node were to reserve a buffer that can handle 513 messages ($512 = 64 \times 8$ for requests for rendezvous, 1 for ack/nack) and the buffer pool is managed as a resource shared by all the 1024 shared lines, forward progress can be assured per each shared line per each remote node.

7 Related Work

Chandra *et al* [CRL96] use a model based on continuations to help reduce the complexity of specifying the coherency protocols. The specification can then be model checked and compiled into an efficient object code. In this approach, the protocol is still specified at a low-level; though rendezvous communication can be modeled, it is not very useful as the transient states introduced by their compiler cannot adequately handle unexpected messages. In contrast, in our approach, user writes the rendezvous protocol using only the rendezvous primitive, verifies the protocol at this level with great efficiency and compiles it into an efficient asynchronous protocol or object code.

Our work closely resembles that of Buckley and Silberschatz [BS83]. Buckley and Silberschatz consider the problem of implementing rendezvous using message when the processes use generalized input/output guard. However, since the focus of their problem is for implementation in software, efficiency is not a primary concern. Their solution is too expensive for DSM protocol implementations. In contrast, we focus on a star configuration of processes with suitable syntactic restrictions on the high-level specification language, so that an efficient asynchronous protocol can be automatically generated.

Gribomont [Gri90] explored the protocols where the rendezvous communication can be simply replaced by asynchronous communication without affecting the processes in any other way. In contrast, we show how to *change* the processes when the rendezvous communication is replaced by asynchronous communication. Lamport and Schneider [LS89] have explored the theoretical foundations of comparing atomic transactions (*e.g.*, rendezvous communication) and split transactions (*e.g.*, asynchronous communication), based on left and right movers [Lip75], but have not considered specific refinement rules such as we do.

8 Conclusions

We presented a framework to specify the protocols implementing distributed shared memory at a high-level using rendezvous communication. These rendezvous protocols can be efficiently verified, for example using a model-checker. After such verification, the protocol can be translated into an efficient asynchronous protocol using the refinement rules presented in this paper. The refinement rules add transient states to handle unexpected messages. The rules also address buffering considerations. To assure that the refinement process generates an efficient asynchronous protocol, some syntactic restrictions are placed on the processes. These restrictions, namely enforcing a star configuration and restricting the use of generalized guard, are inspired by domain specific considerations.

We are currently studying letting two remote nodes communicate in *asynchronous* protocol so that better efficiency can be obtained. Relaxing the star configuration requirement for the rendezvous protocol does not add much descriptive power. However, relaxing this constraint for the asynchronous protocol can improve efficiency.

We are currently comparing the efficiency of hand-designed migratory and invalidate protocols with those of the refined protocols on benchmark programs.

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