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Experience with a Language for Writing Coherence Protocols

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Abstract. In this paper we describe our experience with *Teapot* [7], a domain-specific language for writing *cache coherence protocols*. Cache coherence is of concern when parallel and distributed computing systems make local replicas of shared data to improve scalability and performance. In both distributed shared memory systems and distributed file systems, a *coherence protocol* maintains agreement among the replicated copies as the underlying data are modified by programs running on the system.

Cache coherence protocols are notoriously difficult to implement, debug, and maintain. Unfortunately, protocols are not off-the-shelf items, as their details depend on the requirements of the system under consideration. This paper presents case studies detailing the successes and shortcomings of using Teapot for writing coherence protocols in two systems. The first system, *loosely coherent memory* (LCM) [16], implements a particular type of distributed shared memory suitable for data-parallel programming. The second system, the *xFS distributed file system* [9], implements a high-performance, serverless file system.

Our overall experience with Teapot has been very positive. In particular, Teapot's language features resulted in considerable simplifications in the protocol source code for both systems. Furthermore, Teapot's close coupling between implementation and formal verification helped to achieve much higher confidence in our protocol implementations than previously possible and reduced the time to build the protocols. By using Teapot to solve real problems in complex systems, we also discovered several shortcomings of the Teapot design. Most noticeably, we found Teapot lacking in support for multithreaded environments, for expressing actions that transcend several cache blocks, and for handling blocking system calls. We believe that domain-specific languages are valuable tools for writing cache coherence protocols.

1 Introduction

Cache coherence engines are key components in several parallel and distributed computing systems. Coherence is of concern whenever distributed systems make local replicas of shared information for reasons of performance or availability (or both), because systems must keep replicas current as they modify the shared information. Thus, distributed shared memory systems [6,15], distributed file systems [9,20], and high-performance client-server database systems [12] all implement cache coherence protocols. Coherence in web caching is also a current research topic in the distributed systems community [19].

Tools that facilitate the implementation of cache coherence protocols are important for two reasons. First, coherence protocols, while ubiquitous, show a great deal of variety because the protocol for a particular system is closely linked to its sharing semantics and performance goals. For example, different distributed shared memory systems provide different memory consistency models [13], which support different assumptions that application programs can make about the currency of cached values. Moreover, systems with similar sharing semantics can have vastly different protocols that use different algorithms to achieve the same task, albeit with different performance considerations. Thus, each system essentially needs its own coherence protocol.

Second, and perhaps more importantly, cache coherence protocols represent complex, distributed algorithms that are difficult to reason about, and often contain subtle race conditions that are difficult to debug via system testing. Furthermore, to our knowledge, previous systems have not attempted a clear separation between the cache-coherence engine and other implementation

details of the system, such as fault management, low-level I/O, threads, synchronization, and network communication. It is not difficult to imagine the hazards of this approach. The implementor cannot reason about the coherence protocol in isolation from other details, and any modification she makes in the system can potentially impact the protocol's correctness—a debugging nightmare. Experimentation with newer protocols is a perilous proposition at best.

Teapot is a protocol writing environment that offers two significant improvements over writing ad-hoc C code. First, it is a domain-specific language specifically targeted at writing coherence protocols. As such, it forces a protocol programmer to think about the logical structure of a protocol, independent of the other entanglements of a system. The language features of Teapot easily express the control structures commonly found in coherence protocols. Second, Teapot facilitates automatic verification of protocols because it not only translates Teapot protocols into executable C code, but also generates input code for MurΦ, an automatic verification system from Stanford [10]. MurΦ can then be used to detect violations of invariants with a modest amount of verification time. For example, our system might report a stylized trace of a sequence of events that would cause a deadlock. A protocol can be run through a verification system prior to actual execution, to detect possible error cases, *without* having to manually rewrite the protocol in MurΦ's input language.

The Teapot work was originally undertaken to aid protocol programmers for the Blizzard distributed shared memory system [25]. Blizzard exports a cache-coherence protocol programming interface to an application writer, so she can supply a coherence protocol that best suits the requirements of her application. Writing such protocols in C, without domain-specific tools, turned out to be a difficult task, fraught with problems of deadlocks, livelocks, core dumps, and most annoyingly, wrong answers. After a few initial protocols (all variants of conventional shared memory protocols) were successfully developed using Teapot, the Blizzard team at Wisconsin wrote several other, more complicated coherence protocols for their system. We report on one such protocol here. Subsequently, the xFS team at UC Berkeley adopted Teapot to write the coherence protocol for their distributed file system. As expected, these teams encountered several rough spots, because the original Teapot design did not anticipate all of the requirements of other protocols in the context of Blizzard, much less those arising in a distributed file system context.

This paper describes our experiences with using Teapot to implement the coherence engines in two distinct systems. In both systems, we found Teapot to be vastly superior to earlier efforts to implement the protocols using C without domain-specific tools. The paper makes several contributions. First, it highlights the aspects of Teapot that proved successful across several protocols:

- *Domain-specific language constructs*, such as a state-centric control structure and continuations, simplified the protocol writing task.
- *Automatic protocol verification* using the MurΦ system improved system confidence and reduced testing time.

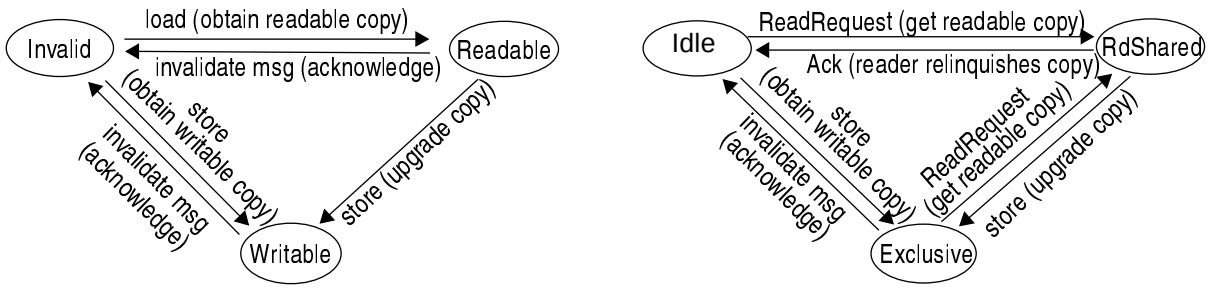
Perhaps more importantly, this paper also discusses shortcomings of the language that became apparent only when we attempted to develop protocols that were more complicated than the simple protocol examples on which Teapot was originally tested. In particular, our experience indicates that improved support for multi-threaded environments, for protocol actions that affect multiple blocks, for local protocol actions that might block, and for automated verification test strategies would further ease the job of a protocol designer. Finally, the paper generalizes our experience to provide guidelines for future domain-specific languages for systems software.

The rest of the paper is organized as follows. Section 2 provides some basic background on cache coherence protocols and describes the implementation problems generally faced by protocol programmers. Section 3 introduces the language features in Teapot that address the difficulties presented in Section 2. Section 4 presents the case-study of LCM, and Section 5 presents the case-study of xFS. Section 6 describes some related work. Section 7 concludes the paper with implications for domain-specific languages for systems software.

2 Coherence Protocols and Complications

In systems with caching, read operations on shared data typically cache the value after fetching it from remote nodes, in the expectation that future read references will "hit" locally. Write operations on shared data must take steps—coherence actions—so readers with cached values do not continue to see the old value indefinitely. This section describes coherence protocols in more detail in the context of distributed shared-memory systems, though the issues discussed apply equally well to other contexts with appropriate changes in terminology.

Shared-memory systems can be implemented using a pair of mechanisms: access control and communication. Access control allows the system to declare which types of accesses to particular regions of memory are permitted. These permissions typically include: no access (*invalid*), reads only (*readonly*), and both reads and



(a) (b)

Figure 1: Idealized protocol state machine for (a) the non-home side, and (b) the home side. Transitions are labeled with causes and, in parentheses, actions.

writes (*readwrite*). Performing an illegal access (for example, writing a *readonly* region) causes an *access fault* and invokes the coherence protocol. Communication allows a system to exchange control information and data between processors. The coherence protocol comes into play at an access fault. It must obtain a copy of the referenced data with appropriate access permissions and satisfy the access. Many protocols designate a *home node* that coordinates accesses to a particular range of memory addresses. The faulting processor sends a request to the home node for a copy of the required data, which responds with the data after updating its bookkeeping information. After receiving the response, the faulting processor typically caches the data so subsequent accesses will succeed without communication.

A common technique for ensuring coherence allows at most a single writer or multiple readers for any block of memory at a time. When the home receives a request for a writable copy of the block, it asks processors currently holding a readable copy to invalidate it, i.e. allow no further accesses. A writable copy can then be sent to the requestor. A cache coherence protocol specifies the actions taken by the home and caching processors in response to access faults and incoming messages. These actions are commonly captured by finite state machines, with transitions between protocol *states* occurring in response to faults and messages. Figure 1 shows sample state machines describing protocol actions for a caching processor and the corresponding home side. Both the home and caching processors associate a state with each memory block. At an access fault or upon a message arrival, the protocol engine consults the appropriate block's state to determine the correct action. Typical protocol actions involve sending messages and updating the state, access permissions, and contents of a memory block. Home nodes also maintain a *directory*, a per-block data structure that usually keeps track of which processors have a readable copy, or which processor has an exclusive copy.

As an example, consider a (non-home) block that is initially in the *Invalid* state. A processor reading any address within the block causes an access fault, at which time the protocol is invoked. Its action is to send a request to the home node for a readable copy and await a response. Assuming no outstanding writable copy exists (the *Idle* state in Figure 1), the home responds with a readable copy and changes its state to *ReadShared*. The arrival of this message on the non-home side causes the protocol to copy the incoming data to memory and change the block's state to *Readable* (and access permissions are changed from *invalid* to *readonly*).

Unfortunately, specifying protocols is much more difficult than the simple three-state diagrams in Figure 1 would lead one to believe. The main difficulty is that, although the transitions shown *appear* to be atomic, many state changes in response to protocol events cannot be performed atomically. Consider the transition from the *Exclusive* state to the *ReadShared* state in Figure 1. Conceptually, when a request arrives in the *Exclusive* state for a readable copy of a block, the protocol must retrieve the exclusive copy from the previous owner and pass it along to the requestor. The protocol sends an invalidation request to the current block holder, and must await a response before proceeding. But, to avoid deadlock, protocol actions must run to completion and terminate. This requires that an intermediate state, *Excl-To-ReadShared* (*Excl-RS* for short), be introduced. After sending the invalidation request, the protocol moves to the *Excl-RS* state and relinquishes the processor. When the invalidation acknowledgment arrives in this intermediate state, the processor sends a response to the original requestor and completes the transition to *ReadShared*. A revised state diagram incorporating the required intermediate states is shown in Figure 2 (which is still far removed from a realistic protocol).

Introducing intermediate states increases the number of states a programmer has to think about. Furthermore, while in an intermediate state, messages other than the expected reply can arrive. For example, before the inval-

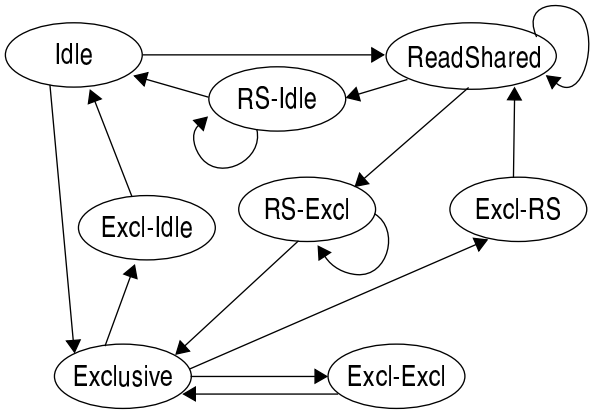


Figure 2: State machine (home side) with intermediate states necessary to avoid synchronous communication.

idation response arrives in the *Excl-RS* state, another request for an exclusive copy could arrive from a different processor. A protocol designer must anticipate the arrival of such unsolicited messages and handle them in an appropriate manner. It may be tempting to not take such messages out of the network while they are not welcome: this, however, is not an option on most systems, because messages must constantly be drained from the network to avoid deadlock in the network fabric [27].

Message reordering in the network adds to the woes of a protocol programmer. For example, processors may appear to request copies of cache blocks which they already have, if a read request message overtakes an invalidation acknowledgment message in the network. The protocol might have to await delayed messages before deciphering the situation and determining the correct action. Without machine assistance, anticipating all possible network reorderings is a very difficult task!

The traditional method of programming coherence state machines usually resorts to ad-hoc techniques: unexpected messages may be queued, they may be negatively acknowledged (nack'ed), or their presence may be marked by a "flag" variable. Additional flag variables are often used to track the out-of-order arrival of messages as well. These techniques invite protocol bugs. Queuing can easily lead to deadlocks; similarly, nack'ing can lead to livelocks or deadlocks. Flag variables are essentially extra protocol state—failing to update or test a flag at all the right places again leads to correctness problems. Moreover, protocols implemented in this style are very difficult to understand and modify.

The case studies presented in sections 4 and 5 show that all these complications were serious issues in the initial state machine versions of those protocols. In the next section, we highlight the features of Teapot that aid a protocol programmer.

3 Teapot

The Teapot language resembles Pascal with extensions for protocol programming support, but fewer built-in types. Space does not permit a complete description of the language; the reader is referred to the original paper [7] for further language details. The Teapot compiler can generate executable C code from a protocol specification, and can also translate it to code that can be fed to the MurΦ verification system [10].

```
1.  State Stache.Home_Exclusive{}
2.  Begin
3.      Message GET_RO_REQ(id:ID; Var info:INFO; src: NODE)
4.      Var
5.          itor : SHARER_LIST_ITOR;
6.          j : NODE;
7.      Begin
8.          Send(GetOwner(info), PUT_DATA_REQ, id);
9.          IncSharer(info, src);
10.         Suspend(L, SetState(info, Home_Excl_To_Sh{L}));
11.         -- send out a readable copy to all nodes that want a copy
12.         -- (more nodes might want a copy while you were waiting)
13.         Init(itor, info, NumSharers(info));
14.         While (Next(itor, j)) Do
15.             SendData(j, GET_RO_RESP, id, TPPI_Blk_No_Tag_Change);
16.         End;
17.     End;
18.     -- other messages ...
19.     Message DEFAULT(id:ID; Var info: INFO; src: NODE)
20.     Begin
21.         Error("Invalid message %s to Home_Exclusive",Msg_To_Str(MessageTag));
22.     End;
23. End;
```

Figure 3: Teapot example

```
1.  State Stache.Home_Excl_To_Sh{C:CONT}
2.  Begin
3.      Message PUT_DATA_RESP (id: ID; Var info: INFO; src: NODE)
4.      Begin
5.          RecvData(id, TPPI_Blk_Validate_RW, TPPI_Blk_Downgrade_RO);
6.          SetState(info, Home_RS{});
7.          Resume(C);
8.      End;
9.      -- other messages
10.     Message DEFAULT (id: ID; Var info: INFO; src: NODE)
11.     Begin
12.         Enqueue(MessageTag, id, info, src);
13.     End;
14. End;
```

Figure 4: Teapot example (cont'd)

3.1 Language Features

A Teapot program consists of a set of states; each state specifies a set of message types and the actions to be taken on receipt of each message, should it arrive for a cache block in that state. We exhibit some of the features of Teapot using an example. The Teapot code in Figure 3 implements coherence actions for a block in the *Exclusive* state at the home node. Suppose the block receives the request message `GET_RO_REQ`, asking for a readable copy. The action code for this message first sends a `PUT_DATA_REQ` message to the current owner (note that the variable `info` is a pointer to the directory data structure). Next, it executes a `Suspend` statement. A `Suspend` statement is much like a "call-with-current-continuation" of functional programming languages. Syntactically, it takes a program label (`L`), and an intermediate state (`Home_Excl_To_Sh`) which it visits "in transition". The second label, `{L}`, specifies where execution should resume upon return, and can differ from the first argument. Operationally, `Suspend` saves the environment at the point it appears in a handler body and effectively puts the handler to sleep. This mechanism is used to provide a blocking primitive inside a handler, which physically needs to relinquish the processor every time it is invoked

What happens in the intermediate state? Figure 4 shows the Teapot code executed when a `PUT_DATA_RESP` message arrives. The handler receives the up-to-date content of the cache block from the network, sets its own state to *ReadShared*, and executes a `Resume` statement. The `Resume` is the equivalent of a "throw" for a "call-with-current-continuation" of functional programming. Syntactically, it takes a continuation parameter (`C`) as an argument. (Note from line 1 in Figure 4 that the continuation variable `C` is a state parameter and is a part of the environment visible to all the message handlers in that state.) Operationally, it restarts a suspended handler immediately after the `Suspend` statement whose label is captured in `C`. Thus, after the `Resume` statement, `GET_RO_RESP` messages are sent to the set of requesters (see Figure 3 again, lines 13-16). Continuations in Teapot let us avoid having to manually decompose a handler into atomically executable pieces and sequencing them. Further advantages of the `Suspend/Resume` primitives are brought out in the case studies.

Teapot provides a mechanism for handling unexpected messages by queuing. It does not solve the problem of deadlocks directly, but facilitates deadlock detection via verification. In lines 10-13 of Figure 4, all messages not directly handled (`DEFAULT`) are queued for later execution—these messages are appropriately dispatched once the system moves out of an intermediate (*transient*) state.[1] Teapot relies on a small amount of system-specific dispatch code to deliver incoming network messages and previously queued messages, based on a state lookup and the message tag. Note that the `DEFAULT` messages in Figure 3 flag an error because these messages cannot occur in a correctly functioning system.

3.2 Verification Support

Teapot makes no attempt to verify protocols, but translates protocols into code for the MurΦ automatic verification system [10]. MurΦ explores all possible protocol actions by effectively simulating streams of shared-memory references, and ensuring that no system-wide invariants are violated. If unanticipated messages arrive or deadlock occurs, Teapot transforms the MurΦ error log into a stylized diagram of the protocol events leading to the violation.

Three basic components are required for verification: A MurΦ description of the protocol under test, MurΦ code implementing all types and subroutines used by the protocol, and a *ruleset* describing legal sequences of protocol events. While only the first component is generated by Teapot, examples of the remaining pieces are included with Teapot and can often be reused without modification. User intervention is required only if new

1. Users must declare which states are transient.

types or routines are added, or the protocol being developed only handles stylized streams of protocol events. The latter scenario is described in more detail in the following section.

4 LCM

The Loosely Coherent Memory (LCM) coherence protocol [16] provides sequentially-consistent distributed shared memory as a default, and is similar in many respects to protocols like DASH [18], Alewife [1], and Stache [24]. The key difference is that LCM allows global memory to become temporarily inconsistent under program control. During such phases, a given data item may intentionally have different values on different processors. This makes management of shared data more difficult. Memory is returned to a globally-consistent state by merging distinct versions of each data item and ensuring that all processors see the new values. This requires coordination among all processors in the system, and mixes computation (merge functions) with traditional protocol actions.

LCM implements the semantics of the data-parallel programming language C** [17] faster than conservative, compiler-implemented approaches. C** semantics specify that parallel function invocations on aggregate data do not interact. LCM enforces these semantics by keeping shared-data modifications private until all parallel invocations complete, then returns the system to a consistent state. Processes can still collaborate to produce values via a rich set of reduction operations (including user-specified reductions), but the results of these reductions are not available until after all parallel function invocations finish.

4.1 Initial Implementation

Our first LCM implementation effort was undertaken without the support of any formal methods or tools. The C-code source of the Stache (ordinary shared memory) protocol was available to us, so we used it as a starting point, adding extra LCM functionality as required. In retrospect, starting with Stache was an unfortunate decision. Stache, while a relatively simple protocol design, is still a large and complex piece of software. Adding LCM functionality required both that the behavior of existing protocol states be altered and that new states be added—a difficult proposition for the unaided programmer. Small changes in existing states (and the addition of a new states) often had far-reaching effects that were difficult to fully anticipate.

It took several months for a single graduate student, working full-time, to complete the basic protocol modifications, after which a debugging phase began. It took roughly as long to debug the modified protocol as it did to write it in the first place, since the protocol was riddled with subtle timing-related bugs, the result of the unpredictable effects of our modifications. A suite of applications was used to debug the protocol—each application exercising a new set of path-specific bugs in LCM which had to be isolated, understood, and repaired. It often took days to identify infrequently-occurring bugs, and the resulting "fixes" many times introduced new bugs. Even after the LCM protocol had achieved relative stability, user confidence in its correctness was low.

4.2 Teapot and LCM

An early version of the Teapot system was ready for testing as debugging of the hand-written LCM protocol was being completed, and LCM was reimplemented with Teapot to more thoroughly evaluate the system. The Teapot environment was a vast improvement over the hand-coded approach. We found two language features of Teapot particularly useful: the "state-centric" programming model, and the use of continuations to allow blocking operations in handler code.

Teapot enforces a protocol programming style that is easier to read and debug than that we used in C. Teapot code is organized by protocol states, each of which contains a list of handlers to be run for messages arriving in that state. This contrasts with the handwritten protocol's "message-centric" approach, where large handlers were written for each message type and selected different action code to run based on the protocol's state. Organizing the protocol by states makes it easier to express and implement for several reasons. First, each handler is now a smaller unit of code, since a self-contained handler is written for each combination of message and block state. Second, grouping handlers by state instead of message type keeps related information close together: A state's behavior can be understood by scanning a set of consecutive handlers, instead of looking through the entire protocol. Of course, in retrospect, we could have adopted a state-centric organization in the handwritten protocol, but the C language did not make the benefits of doing so immediately obvious while the Teapot system enforced a disciplined programming style that utilized the better design choice.

Teapot's continuations also made an enormous improvement in handler legibility. Even for handlers using a single `Suspend` statement, keeping the code on either side of the call in the same handler dramatically increased

```
1.  State LCM.Home_Excl {}
2.     ... other messages
3.     Message GET_RO_REQ (id: ID; Var info: INFO; src: NODE)
4.     Begin
5.        [...]
6.        If (SameNode(src, GetOwner(info))) Then
7.           Suspend(L, SetState(info, Home_Excl_To_Idle{L}));
8.           If (SameState(GetState(info), Home_Idle{})) Then
9.              SetState(info, Home_RS{});
10.             AccChg(id, TPPI_Blk_Downgrade_RO);
11.          Else
12.             If (InSharers(info, src)) Then
13.                Suspend(L2, SetState(info, Home_Await_PUT_ACCUM{L2}));
14.             Endif;
15.          Endif;
16.          [...]
17.       Else
18.          Send(GetOwner(info), PUT_DATA_REQ, id);
19.          Suspend(L1, SetState(info, Home_Excl_To_Sh{L1}));
20.          IncSharer(info, src);
21.       [...]
22.       Endif;
23.    [...]
24.    End;
```

Figure 5: Teapot handler code containing multiple `Suspend` statements

readability. Some handlers used as many as three `Suspend` statements, and therefore had to be split into multiple code fragments in the handwritten version. Figure 5 shows part of an LCM handler with three `Suspend` statements. Without continuations, this code would have been split into at least four distinct handlers making it much harder to write and debug. Teapot also allows dynamic nesting of continuations, a feature used numerous times during the specification of LCM. For example, the first `Suspend` in Figure 5 moves to the `Home_Excl_To_Idle` state, where other handlers (not shown) may suspend again to await delayed messages.

Even with the cleaner design, we uncovered a total of 25 errors using automatic verification. (Each error was fixed as soon as it was detected and understood, and the verification step was repeated.) Many of these were subtle bugs that were unlikely to occur often in practice, but were all the more dangerous as a result. Figure 6 illustrates an LCM bug that is representative of those found through verification. Both diagrams show messages being exchanged between a pair of processors, with time increasing from top to bottom. In each case, a preceding exchange of messages (not shown) has left the cache (non-home) side with the exclusive copy of a given coherence block.

In Figure 6a, the caching processor performs an LCM modification of the block, creating a version that is inconsistent with respect to other copies in the system. However, since the cache side held the exclusive copy at the time it performed the modification, it first sends a *copy* of the block home. This data can be used by the home to respond to requests for the block from other processors. The block is returned home via a `PUT_MOD` message when the cache side is finished. The second LCM modification then faults and requests the block back from the home.[1] Messages have been reordered in the network such that the first to appear at the home is the request for data. The home detects the reordering, since it knows the requestor already *has* a copy of the block. The correct action in this case is to await the `SHARE_DATA` message, then satisfy the request. The home leaves the block in the `Home_LCM` state to denote the fact that at least one processor has created its own version of the block.

Initially, we thought the arrival of the `GET_RO_REQ` in the `Home_Excl` state always implied the message reordering scenario in Figure 6a, and both the hand-written version of LCM and the first Teapot version encoded this assumption. Unfortunately, in the more complicated case shown in Figure 6b, this caused the protocol to respond incorrectly. The home should instead await the `PUT_DATA_RESP` message, transition to the `Home_Idle` state, and satisfy the request. Correcting the protocol is straightforward once the two scenarios have been identified, but it is unreasonable to expect an unaided programmer to have foreseen such a bug, due to the complexity of the cases involved. Enumerating all chains of protocol events and ensuring that they are

1. This scenario arises frequently in applications where a given processor handles several of a set of parallel tasks consecutively.

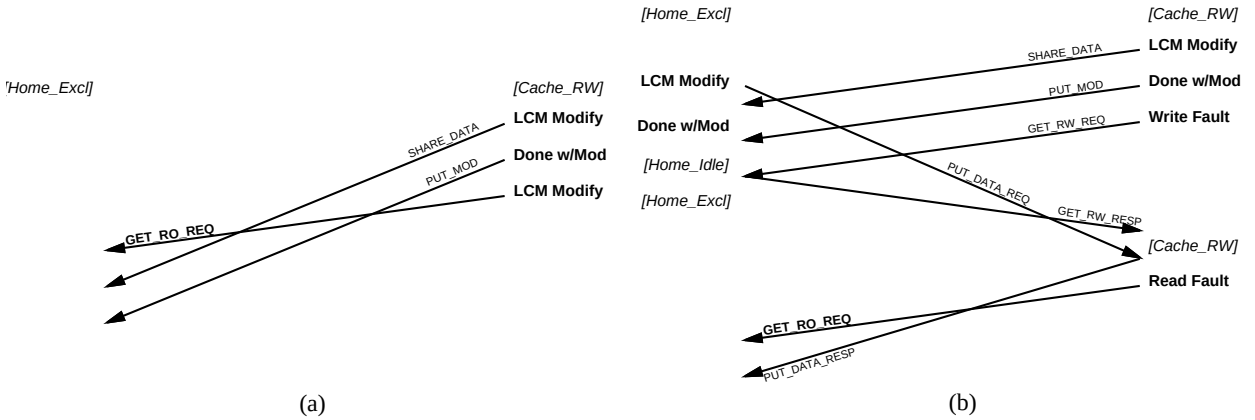


Figure 6: Two different scenarios in which a `GET_RO_REQ` arrives in state `Home_Exclusive`. The appropriate response to the message is different in each case.

properly handled is a job much better handled through verification.

Using Teapot, the new version of the LCM protocol was written, verified, and running applications in two weeks' time. Only one bug was uncovered during field testing of the new protocol, and it occurred in a simple support routine that was intentionally *not* simulated.[1] Also, because of Teapot, we were able to implement easily three variants of LCM: one that eagerly sends updates to consumers at the end of an LCM phase, another that manages extra, distributed copies of some data as a performance optimization, and a version that incorporates both of these features.

4.3 Teapot Shortcomings

While Teapot made it significantly easier to get LCM written and working, it fell short of our needs in several respects. One significant obstacle is Teapot's inability to perform actions across a *set* of blocks. A message handler, for example, can only update the state of the block to which a message is directed. In LCM, action must periodically be taken across a collection of blocks. For example, during a merge phase, a processor returns *all* modified blocks to their homes, where they are combined with copies from other processors. An event handler was written to carry out this flushing operation for a single block, but the handler must somehow be invoked for each block returned. As an application runs, the LCM protocol constructs a list of modified blocks that require flushing at the next reconciliation. This list is traversed when the reconciliation phase begins, and the appropriate event handler invoked on each block. Additional C code was written to traverse the list and invoke handlers in the executable version of the protocol, but this code is outside the scope of the Teapot protocol specification and therefore cannot be verified. The workaround in Teapot was to structure the MurΦ ruleset so that, during a reconciliation, it invoked the handlers for each block in the list. This restructuring significantly increased the complexity of the ruleset and therefore the chances that it could contain an error.

Even without operations on sets of blocks, the ruleset for LCM was already much more complicated than those for our previous protocols. Unlike Stache, where any arbitrary stream of interleaved loads and stores to shared memory must be handled, LCM only properly handles stylized sequences of loads and stores. There are distinct phases that all processors must agree to initiate, in which only certain access patterns are legal. Encoding this into a ruleset was a lengthy, complicated, and potentially error-prone process, and represented a significant fraction of the work required to implement LCM. It would be preferable to generate such rulesets automatically from a high-level description of a protocol's memory model, but we currently are unaware of any techniques for doing so.

The last shortcoming was relatively minor. Teapot currently does not allow the testing of a pair of expressions for equality. There were several places in the protocol where pairs of states or node identifiers needed to be compared, and an external routine had to be written to perform these tests. Future releases of Teapot should consider extending the language such that simple comparisons can be done without resorting to external procedures.

5 xFS

xFS, a network file system described in several previous papers [2,9], is designed to eliminate all centralized bot-

1. The routine was deemed too simple to be hiding any bugs.

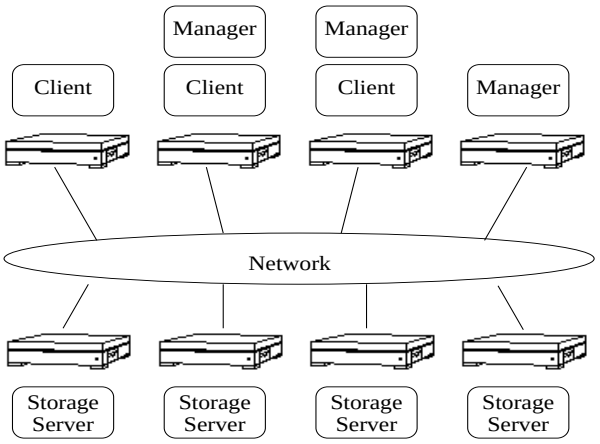


Figure 7: A sample xFS configuration. Clients, managers, and storage servers provide a global memory cache, a distributed metadata manager, and a striped network disk respectively.

tlenecks and efficiently use all resources in a network of workstations. One of the most important features of xFS is its separation of data storage from data management. This separation, while offering superior performance and scalability compared to traditional file systems, also requires a more sophisticated cache coherence protocol. In addition, other aspects of the cluster file system environment—such as multi-level storage and reliability constraints—further complicate the system compared to more traditional DSM coherence protocols. Due to these aspects of the design, we found it difficult to implement a correct protocol with traditional methods. The use of Teapot has resulted in clearer abstraction levels, increased system confidence, and reduced complexity in the implementation of cache coherence in xFS. At the same time, there are significant differences between xFS and the original applications which Teapot was designed to support. These differences have revealed some shortcomings of Teapot.

5.1 Caching in xFS

The three main components of an xFS system are the *clients*, the *managers*, and the *storage servers*. Under the xFS architecture, any machine can be responsible for caching, managing, or storing any piece of data or metadata by instantiating one or more of these subsystems. Figure 7 shows a sample xFS installation.

Each of the three subsystems implements a specific interface. A client accepts file system requests from users, sends data to storage servers on writes, forwards reads to managers on cache misses, and receives replies from storage servers or other clients. It also answers cooperative cache forwarding requests from the manager by sending data to other clients. The job of the metadata manager is tracking locations of file data blocks and forwarding requests from clients to the appropriate destinations. Its functionality is similar to the directory manager in traditional DSM systems. Finally, the storage servers collectively provide the illusion of a striped network disk.

xFS employs a directory-based invalidate cache coherence protocol. This protocol, while similar to those seen in traditional DSM systems, exhibits four important differences that prevent xFS from using previously developed protocols and that complicate the design of xFS. (1) xFS separates data management from data storage. Although this separation allows better locality and more flexible configuration, it splits atomic operations into different phases that are more prone to races and deadlocks. (2) xFS manages more storage levels than traditional DSM systems. For example, it must maintain the coherence of the kernel caches, write-ahead logs, and secondary storage. (3) xFS must maintain reliable data storage in the face of node failures, requiring protocol modifications that do not apply to DSM systems. For example, a client must write its dirty data to storage servers before it can forward it to another client. (4) The xFS client is heavily multi-threaded and it includes potentially blocking calls into the operating system, introducing more chances for synchronization errors not seen in DSM systems.

5.2 Implementation Challenges

The xFS design and environment make the implementation and testing of cache coherence in xFS more difficult than in most systems. The usual problems of proliferation of intermediate states and subtle race conditions were even worse for xFS, as described below.

5.2.1 Unexpected Messages and Network Reordering

An xFS node can receive messages that cannot be processed in its current state. This is also a problem in most DSM coherence systems, but it is particularly pervasive in xFS because xFS separates data storage and control, thereby making it difficult to serialize data transfer messages and control messages with one another: data transfer messages pass between clients and storage servers or between clients and clients, while control messages pass between clients and managers or storage servers and managers.

The xFS protocol also suffers from the message reordering problems mentioned in Section 2. Further compounding the problem, this protocol often allows multiple outstanding messages in the network to maxi-

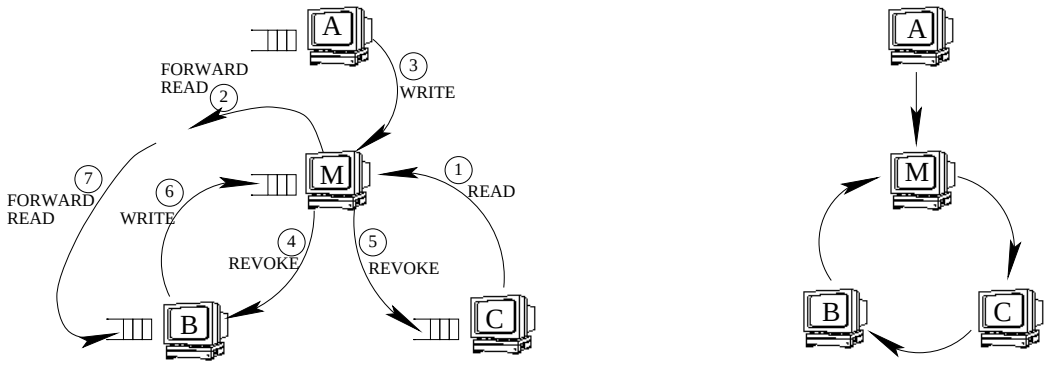


Figure 8: A sample deadlock discovered by the protocol verifier. The three clients are labeled with "A", "B", and "C". The manager is labeled with "M". In Figure (a), arrows denote the directions of the messages. The numbers denote the logical times at which messages are sent and/or received. Shown to the left of each host is a message queue, which holds the requests that are waiting to be processed. Messages that are not queued are processed immediately. In Figure (b), arrows denote the wait-for relationship, and the presence of a cycle indicates a deadlock.

mize performance. For example, an xFS manager does not wait until a client completes a forwarding request to continue, so a subsequent invalidate message can potentially reach the same client out of order. Although such ordering can be enforced at the communication layer [5], recent research has argued that this ordering is best expressed with application state [8]. Furthermore, even if the network ensured in-order messages between nodes, the causes mentioned in the previous paragraph would still require xFS to explicitly handle unexpected message arrivals.

5.2.2 Software Development Complexity

Managing the large number of states needed to implement the xFS state machine was a challenge. Although, intuitively, each block can be in one of only four states—*Read Shared*, *Private Clean*, *Private Dirty*, or *Invalid*—the system must, in fact, use various transient states to mark progress during communication with the operating system and the network. Dealing with unexpected or out of order messages, handling the separation between data storage and data management, maintaining multiple levels of storage hierarchy, and ordering events to ensure reliable data storage increases the number of transient states needed to handle xFS events. Even a simplified view of the xFS coherence engine contains twenty-two states. One needs a systematic approach when dealing with such a large state space.

As we were implementing the protocol, it became clear that the C language was too general. Despite our best intentions, aspects of implementations that were not related to protocol specification were mixed in. The result was less modular, harder to debug, and harder to maintain. Although the xFS protocol is similar to many other DSM protocols, we have found it non-trivial to reuse or modify existing codes, due to their ties to their native environments.

5.3 Teapot and xFS

After several unsuccessful attempts at completing the cache coherence protocol using traditional development methods, we decided to rewrite the system with Teapot. Our experience with this domain specific language has been positive. In particular, the close ties between Teapot and the MurΦ verification system have provided us with an effective testing tool for attacking the problem of unexpected event ordering; many of the bugs we found and corrected would have been extremely difficult to isolate through field testing alone. Furthermore, several aspects of the Teapot language have simplified the engineering complexity in our system.

5.3.1 Testing for Unexpected Event Orderings

Figure 8 shows an example of a bug in an early version of the xFS protocol that would have been difficult to isolate via field testing, but which MurΦ easily discovered. In this version of the protocol, we saw no need for the manager to maintain sequence numbers for its outgoing messages. If a receiver of a manager request was not ready to act upon it, it simply queued it for later processing. MurΦ found the following deadlock bug:

Initially, client B is the sole cacher of a clean block. (1) Client C sends a read request to the manager. (2) The manager forwards the request to client B. To indicate that Client B should send the data to Client C via cooperative caching, the manager also updates its state to indicate that both client B and C are caching the data.

(3) Meanwhile, client A sends a write request to the manager. (4) The manager sends a revoke request to client B, which arrives at client B before the previous forwarding message, invalidating its data. (5) The manager sends a second revoke request to client C, which client C queues, because its requested data has not arrived. (6) Client B sends a write request to the manager, which the manager queues, because its previously sent revoke message has not been acknowledged. (7) The delayed forward message from step 2 finally arrives, which client B queues, because its request to the manager has not been satisfied. Now we have finally reached a deadlock: client A is waiting for the manager to complete the revoke operations; the manager is waiting for client C to acknowledge the revoke request; client C is waiting for client B to supply the desired data; and client B is waiting for the manager to process its write request. One solution is to use sequence numbers to order the outgoing messages for a particular block from the manager, so the sequence of events seen by any client is consistent with the manager's view.

5.3.2 Reduced Software Development Complexity

Several aspects of the Teapot language simplified the engineering of xFS. Teapot's continuations significantly reduced the number of states needed by xFS's protocol by combining each set of similar transient states into a single continuation state. By being more restrictive as well as more stylized than C, Teapot eliminated a source of programming errors. The domain-specific language also forced the decoupling of the coherence algorithm from other details of the system. This resulted in more modular protocol code that is well isolated from the rest of the file system. Finally, the domain-specific language encouraged software reuse by isolating features that are common to the class of problems they are designed to solve. In our case, we were able to borrow many support structures, such as message queues and state tables, from other protocols supplied with the Teapot release, further reducing complexity and chances of errors.

5.4 Teapot Shortcomings

Teapot was designed and is best suited for DSM environments in which the primitives available to protocol handler writers are limited and simple. The xFS coherence engine, on the other hand, must interact with other components of the system such as the kernel and the active message subsystem via more powerful operations like system calls and thread synchronizations. This difference in terms of the power and expressiveness of handler primitives has revealed some shortcomings of Teapot that were not apparent in its original application domain.

The first shortcoming is the lack of support for multithreading. An xFS client is heavily multithreaded to support concurrent users and react to concurrent requests from the network, but the coherence engine generated by Teapot has a large amount of global state and is difficult to make thread-safe. Transforming the resulting Teapot coherence engine into a monitor was unsuccessful, as subtle thread deadlocks occurred when different xFS threads enter the coherence engine and other xFS modules in different orders.

The second shortcoming concerns blocking operations on local nodes, which occur frequently in xFS coherence handlers. For example, when an xFS client needs to invalidate a cached file data block, it makes a system call to invalidate the data cached in the kernel. This system call might block, waiting for some other event that requires the attention of the coherence engine. Although Teapot provides good support for blocking operations waiting for remote messages, using the same mechanism to handle local blocking operations is tedious. In the above example, one must split the synchronous system call into asynchronous phases, invent a new node to represent the kernel, invent new states for the kernel node, invent new messages the kernel must accept and generate, and write to tie all these elements together. Better support for local blocking operations would have significantly eased the xFS protocol implementation.

The third shortcoming concerns users' inability to add new arguments to Teapot handlers. We were faced with the unpleasant dilemma of either modifying Teapot itself or simulating additional arguments via global variables. The former suggests a limitation of the model; the latter work around is bad software engineering and, in particular, it makes the multithreading problem worse. A more severe restriction is Teapot's lack of support for operations that affect blocks other than the block on which the current message arrives. The problem arises, for example, when servicing the read fault of one block by an xFS client requires the eviction of a different block. This is similar to the problem encountered by LCM during its merging phase.

6 Related Work

The Teapot work most closely resembles the PCS system by Uehara et al. at the University of Tokyo [26]. They described a framework for writing coherence protocols for distributed file system caching. Unlike Teapot, they use an interpreted language, thus compromising efficiency. Like Teapot, they write protocol handlers

with blocking primitives and transform the program into a message-passing style. Our work differs in several aspects. Teapot's continuation semantic model is more general than PCS's, which is a message-driven interpretation of a protocol specification. PCS's application domain is less sensitive to protocol code efficiency, so they do not explore optimizations. Finally, we exploit verification technology by automatically generating an input specification for the MurΦ verification system.

Synchronous programming languages, such as ESTEREL [4] and the Statecharts formalism [14], are useful for describing reactive systems and real-time applications. The most important commonality between these programming languages and Teapot is that they all are ways of expressing complicated finite-state machines more intuitively than a *flat* automaton. They all support some mechanism for composing smaller, simpler state machines at the language level. A compiler then converts this composition into a flat automaton, which the programmer never has to deal with directly. ESTEREL supports decomposition of a larger state machine into smaller, concurrently-running state machines that communicate synchronously. Statecharts support the notions of depth and orthogonality to build large state machines out of smaller ones. Teapot manages the cross-product interaction (and the resulting state-space bloat) of *explicit* protocol states and pending events by factoring the pending events into states *implicit* in the continuations stack. Teapot shares another feature with ESTEREL and Statecharts in its support for automatic verification.

Teapot differs from synchronous languages in several respects. It does not have a notion of time, so it is not suitable for programming real-time applications. The notion of concurrency in synchronous languages is also different from that in Teapot. In synchronous languages, logical concurrency of state machines is convenient for expressing interacting sub-components; such concurrency is later compiled away to obtain a single-thread program. A Teapot program logically specifies only one state machine. The need for concurrency arises because several such programs are required to run on the same processing resource—they have to interleave their execution (essentially as coroutines).

Wing et al. [28] present an eloquent case for using model checking technology with complex software systems, such as a distributed file system coherence protocols. We also use model checking technology, but our primary focus is on a language for writing coherence protocols, and on deriving executable code as well as the verification system input from a single source. They write the input to the model checker separately from their code, which introduces the possibility of errors.

The design and implementation of domain-specific languages has spurred considerable interest in the systems programming community. Recent work includes instruction-set description languages [3,23], a specification language for automatically generating network packet filters [22], and compiler optimizations for interface description languages [11].

7 Conclusion: Implications for Domain-Specific Languages for Systems Software

It would be gratuitous to reiterate the successes and shortcomings of Teapot. Instead, we present some generalized insight gained from using Teapot. Although our experience is with one domain-specific language, we hope that our observations will be useful for designers of other domain-specific languages, particularly for systems software.

7.1 How big to make the language?

An important consideration when designing a domain-specific language is: how general should the language be? Teapot leans heavily to a minimal language and relies on externally-written routines. For example, it has to call a function `SameNode` to compare two values of the type `NODE`, because we could not decide how far, if at all, we wanted to support equality on opaque types in the language. Another example is whether procedure calls should be a part of the language? If so, are there any restrictions to be observed in the code for the procedures? For example, Teapot does not allow `Suspend` inside called procedures.

More comprehensive languages have the advantage that less code needs to be written in external routines. However, a larger language is harder to learn, harder to implement fully, and could be harder to optimize. While smallness has virtues, a designer should not go overboard and apply senseless restrictions. In Teapot, for example, most users were unhappy about the fixed set of arguments that appeared as handler parameters.

Capturing the commonly-occurring programming scenarios is an important role of domain-specific languages. Teapot, for example, incorporates carefully designed abstractions for waiting for asynchronous messages. However, these abstractions were less effective at capturing the scenario of waiting for asynchronous *events* in general. This kind of waiting in xFS had to be cast into the waiting-for-messages idiom using extra messages. In hindsight, the language could have been designed to support asynchronous events, with messages as a special case of events.

For problem domains where it makes sense, it is imperative to think about automatic verification from the very beginning. In Teapot, for example, we maintained a clear distinction between opaque types and their implementation. In fact, the language has no mechanism to describe the implementation of opaque types. This was done so the verification system and C code could provide an implementation suitable for their purpose, rather than providing a common base implementation which may be poor for both purposes. An example of such an abstract type is a list of sharers, which is implemented using low-level bit manipulation in C, but using an array of enumerated type 0..1 in MurΦ. The cost of this approach is that a programmer (not compiler writer) must supply the implementations, which, fortunately, are reusable.

7.2 Compiler issues

Ideally, language users should only need to know the language definition, not the details of the language implementation. Even popular general-purpose languages fall short of this ideal by great distances, at least for systems software. We have three observations in this regard. First, a language's storage allocation policy should be made clear—programmers generally like to know where in memory particular variables live and what their lifetime is. In Teapot, the storage for state parameters was not clearly defined. It was also not clear to programmers how the memory management of continuation records happened. In fact, in the current implementation, unless `Suspend`s and `Resume`s dynamically match, continuation records leak, as we do not provide garbage collection. Fortunately, most protocols naturally have such balanced `Suspend` and `Resume` paths.

Second, compiler optimizations should be explicitly specified and should be under user control. Even with all the virtues of verification, a systems programmer may need low-level debuggers (perhaps for reasons unrelated to the coherence protocol). A restructuring compiler such as Teapot's makes the generated code harder to trace at runtime. Finally, despite these complications, we believe that aggressive optimizations are essential. In our experience, users are unwilling to compromise efficiency for ease of programming, particularly considering that speed is often the main purpose for distributing a computation.

7.3 Threads

As thread programming becomes commonplace, domain-specific language designers must pay close attention to thread support. Even when the language does not currently support threads, if it is successful, sooner or later users will want multithreading support. The DSL designer, due to her unique knowledge of the internals, should be prepared to provide recommendations, if not a full implementation, of thread support.

The first observation from our experience is that thread support cannot be treated as an afterthought; instead it must be an integral part of the early language design. When we attempted to make Teapot thread-safe as an add-on, we quickly discovered that global state made this an error-prone process. Even though we only introduced a small number of coarse grain locks, they frequently led to subtle synchronization problems because these locks were not exposed at the interface level. They broke abstractions and could easily lead to deadlocks. The second observation concerns the different alternatives that can enable a module written in a domain-specific language to interact with other multithreaded components. We have found that a viable alternative to making Teapot thread-safe is to turn the generated code into a single threaded *event loop* [21]. Instead of allowing multiple threads to execute concurrently in the cache coherence state machine, these threads interact with the single thread of the state machine via events. This approach eliminates unnecessary thread synchronizations inside the state machine.

7.4 Distribution and cost of entry

Most users are reluctant to even install a new programming language, much less learn it. Thus, designers of domain-specific languages should be prepared for considerable hand-holding: provide a very complete set of examples, documentation, and a distribution that builds out-of-the-box. The xFS group found that a set of complete examples was a crucial aid to adopting Teapot. However, Teapot faced two stumbling blocks: we asked our users to go pick up SML/NJ compiler from Bell Laboratories, and the MurΦ system from Stanford. Many people quit at this point, even when we offered to lead them through obstacles. Perhaps clever *perl* scripts could pick up the right software from web. Adding to our difficulties, all pieces of our system—SML compiler, MurΦ compiler, and the Teapot source—were constantly in flux, and it was very difficult to maintain coherence. We see no easy way out of this situation. From the point of view of distribution, it would be best to provide everything in portable C code. However, without drawing upon previously distributed software, we could not have built Teapot in a reasonable amount of time.

7.5 A spade is not a general-purpose earth-shattering device

A tool-builder should be up front about what a tool does and does not do. Despite our efforts, several people thought of Teapot as a verification system, which it is not. In fact, we got an inquiry about Teapot which implied that we have discovered a more practical way of doing model-checking than brute-force state-space exploration! Also, we note that Teapot is not directly suitable for describing hardware cache-coherence controllers because it permits unbounded levels of continuations. We were also asked why Teapot would not be suitable for model-checking systems unrelated to cache-coherence. These observations became apparent when people forced us to think beyond the context of Blizzard style DSMs. One should think carefully about a language's or system's restrictions and why they exist from the beginning, so as not to unnecessarily frustrate potential users.

Finally, we hope our work provides further and concrete evidence that it is better to build application-specific tools than to program complex systems with ad-hoc code. In our experience, it is more profitable to start with a focused domain-specific language or tool that solves a very specific problem to the satisfaction of a small user-community. Language extension and attempts at generalizing the application-domain should be considered only afterwards. Languages and tools with a large scope to begin with run the risk of being useful to no one, because they take much longer to design and implement, and ultimately be less useful to users than a more focused tool.

Availability

Teapot is freely distributed. Please see the Teapot page for the latest version: `http://www.cs.wisc.edu/~chandra/teapot/index.html`, or contact one of the authors.

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