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Dartmouth College Computer Science Technical Report  
PCS-TR96-298

The Dark Side of Risk

(What your mother never told you about Time Warp)

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November 4, 1996

**Abstract**

This paper is a reminder of the danger of allowing “risk” when synchronizing a parallel discrete-event simulation: a simulation code that runs correctly on a serial machine may, when run in parallel, fail catastrophically. This can happen when Time Warp presents an “inconsistent” message to an LP, a message that makes absolutely no sense given the LP’s state. Failure may result if the simulation modeler did not anticipate the possibility of this inconsistency. While the problem is not new, there has been little discussion of how to deal with it; furthermore the problem may not be evident to new users or potential users of parallel simulation. This paper shows how the problem may occur, and the damage it may cause. We show how one may eliminate inconsistencies due to lagging rollbacks and stale state, but then show that so long as risk is allowed it is still possible for an LP to be placed in a state that is inconsistent with model semantics, again making it vulnerable to failure. We finally show how simulation code can be tested to ensure safe execution under a risk-free protocol. Whether risky or risk-free, we conclude that under current practice the development of correct and *safe* parallel simulation code is not transparent to the modeler; certain protections must be included in model code or model testing that are not rigorously necessary if the simulation were executed only serially.

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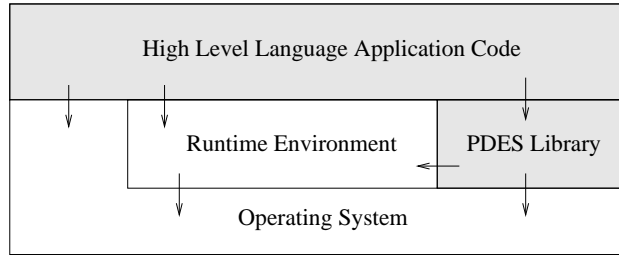


Figure 1: Hierarchy of software layers in typical parallel simulation discrete-event simulation (PDES) package

## 1 Introduction

Reynolds has argued that synchronization protocols for parallel discrete-event simulation are characterized by a spectrum of attributes [10]. In particular, he noted that protocols broadly categorized as “optimistic” really entail two different aspects; *aggressiveness* means executing an event before it is certain to be correct to do so, and *risk* means sending a message that might not be correct. That the two ideas could be separated was demonstrated by Reynolds with a variant on his SRADS protocol [4] the distinction was also used by Steinman in development of the SPEEDES system using the Breathing Time Buckets protocol [12]. Both methods employ aggressiveness, but not risk.

The most widely cited optimistic systems use risk, notably the Time Warp Operating System (TWOS) [6] and Georgia Time Warp (GTW) [3]. The TWOS effort ended some years ago; GTW typifies Time Warp simulators in current use. GTW is essentially a library whose classes and methods can be used in a C or C++ program to transform it into a simulation. One can think of a GTW simulation as code in some high level programming language that calls the GTW libraries, which use Unix facilities. Figure 1 illustrates this layering in the general case. Regions where some state-saving occurs are highlighted.

Optimistic methods are able to recover from temporal errors by saving enough “state” to return them to a prior simulation time. The modeler is responsible for identifying state variables in user code; the Time Warp state is comprised of these variables and some internal state information. Much of the operating environment in which an optimistic simulation executes is not considered to be state, and is not saved or restored. The significance of this fact cannot be overstated. The trend in parallel simulators is to link together simulation libraries, user model code, and user code libraries. The user code libraries in particular may not have been developed for use with optimistic parallel simulation in mind. A case in point is the TeD simulation language being developed at Georgia Tech for the simulation of telecommunication networks; TeD resides astride GTW [1]. Very explicit mechanisms are provided in that tool to link to potentially large blocks of ordinary C/C++ code; the language by design is a “meta-language” that allows certain simulation constructs to be embedded in a high level language. The problem we consider is that under normal Time Warp operating rules, user model code and user libraries may be executed using data arguments that are

utterly inconsistent with the logical state of the code. We will see that the consequences may be that the program crashes (at best), or leads to incorrect behavior or results without hint of error (at worst).

These disturbing consequences are made possible because by accepting risk, Time Warp allows a logical process (LP) to execute a message that is inconsistent with the state of the LP (throughout the paper we will say that the *message* is inconsistent, although the fault of the inconsistency may actually lie with the LP). Such a message is destined to be canceled (or the LP is destined to be rolled back), but the LP has no way of knowing this. Processing the message, the state of the LP is combined with the data in the message to produce potentially nonsensical data and actions that have the ability to corrupt the operating environment in a way that will not be fixed by any rollback. Under the normal Time Warp execution rules there is no way, in general, for the LP to automatically recognize that the message is inconsistent with the LP state.

The dark side of risk, what your mother never told you about Time Warp, is that **every general purpose Time Warp system running today has the potential to behave in this way**. So long as a Time Warp system allows a modeler to include completely general code with the ability to write into non-checkpointed areas such as user library space or runtime system space, that system has an accident waiting to happen.

We have not come to bury Time Warp, but to praise it<sup>1</sup>. For a very important set of real simulation problems, it offers the only hope of high-fidelity parallel simulation. The reason we are emphasizing this particular aspect of Time Warp based simulation is that parallel simulation technology has matured to the point where major complex systems are being proposed that will use it. The complexity of these systems is such that verification and validation just assuming serial execution is a major exercise in software engineering. Our point is that engineering of parallel simulations additionally requires one to ensure the *safety* of the simulation in all states in which it might be placed. We do not believe it is widely understood that this is a larger and more difficult problem for optimistic parallel simulation than it is for serial or conservatively synchronized simulation. But it most certainly is, because the space of potential code states is much larger, and may include states that defy the model semantics or physical constraints of the modeled system.

The threat of this behavior was foreseen by the TWOS designers, and their solution is noteworthy<sup>2</sup>. They recognized that a possible consequence of processing an inconsistent message would be to engage in an action causing a runtime error, e.g., pass a negative value to a square root function, suffer a segmentation fault by indexing outside of array bounds, divide by zero, generate an arithmetic underflow or overflow, etc. . The TWOS system caught Unix signals generated by these occurrences and placed the faulting LP in an “error” state, from which it could be released by a rollback. An error was reported to the user only if the error state was committed, e.g., the GVT passed its time-stamp. This solution goes part way, but is not complete, at least in environments similar to Figure 1. By processing an inconsistent message, an LP can damage the heap, stack, or

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<sup>1</sup> *Julius Caesar*, III.ii, with apologies to Mark Antony.

<sup>2</sup> We acknowledge and thank Peter Reiher and Fred Wieland for providing us with the following description of the TWOS approach to dealing with this problem.

static data area, without generating a signal. The damage may not affect execution until long after its occurrence, and in any case, is permanent.

TWOS was implemented on four platforms (Mark II Hypercube, Mark III Hypercube, BBN Butterfly, UNIX network), the last three fit the model of Figure 1. Interestingly, in the Mark II Hypercube, TWOS was the fundamental operating system and so was better able to protect itself against erratic LP behavior. In all versions dynamic memory management was a touchy issue, so touchy in fact that TWOS programmers were advised to eschew pointers altogether. While the Mark II Hypercube version monitored stack usage (blowing the stack while executing an inconsistent message was a regular occurrence—remember that the Mark II had only 256K memory/node), the later versions did not. The threat of infinite loops was not addressed, although it was thought that this could be handled if a message arrival triggered an interrupt that was permitted to halt the LP’s processing of an event. To our knowledge, GTW does not filter Unix signals nor does it offer protection against any of these possibilities.

This paper first illustrates concretely how this problem can arise and discusses its ramifications, providing a review of a problem long known to Time Warp cognoscente. Our contribution is to explore how to eliminate two sources of the problem—lagging rollbacks and stale state—and then to show that an LP can still be pushed into a state that is inconsistent with model semantics. We look at risk-free protocols, and show that if all LP code is safe with respect to “internal speculation”, then the simulation is safe. Finally, we comment on the ramification of these observations on parallel simulator and on user code.

## 2 The Problem

We encountered the possibility of processing an inconsistent message when using GTW to simulate multicast resource allocation algorithms. In our model, a “link” LP is responsible for storing the current usage and availability of a network link. Such an LP may be queried “how much bandwidth do you have available”, may be instructed “give me  $B$  bits per second bandwidth”, and may be notified “I’m returning  $B$  bits per second bandwidth”. “Node” LPs simulate the arrival of multicast requests; the multicast acceptance procedure involves (i) querying the link LPs that would be involved in the broadcast, analyzing the available bandwidth and (if the broadcast can be accepted) (ii) computing how much bandwidth should be requested from each link, (iii) instructing each link to allocate this computed amount to the broadcast. When the broadcast session is completed, the node LP restores the used bandwidth to the link LPs involved in the broadcast.

This paper resulted from our observation that link LPs with zero available bandwidth were sometimes instructed to allocate some non-zero amount of bandwidth to a new connection, and that link LPs whose bandwidth was completely available were sometimes instructed to add additional available bandwidth.

Close analysis revealed that these nonsensical situations were transient, either the LP was rolled back and when approaching the message again was in a state consistent with the message’s instruc-

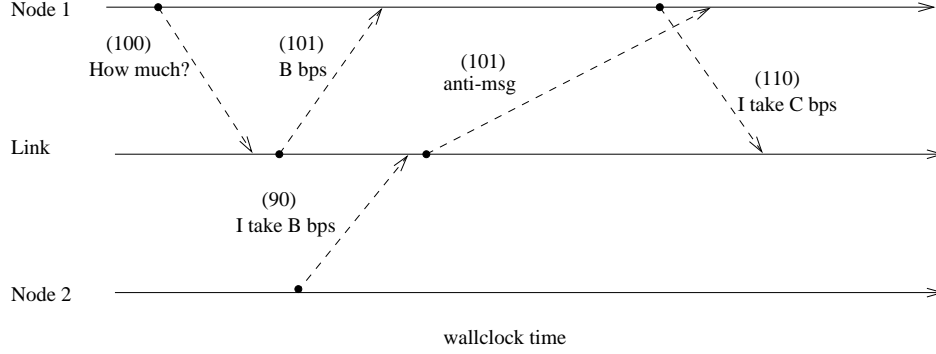


Figure 2: Timing diagram of how an inconsistent message may occur.

tion, or the message itself was annihilated. We also came to understand how these situations could arise. Figure 2 illustrates an example. At (simulation) time 100 a link LP would be queried by node 1 for availability information, and would report its available bandwidth,  $B > 0$ , in response. Then, the link LP is rolled back to an earlier time, say 90, by a message from node 2 that claims all  $B$  bits per second of the available bandwidth at time 90. Node 2 does not release this bandwidth any time soon. As part of the processing of that rollback, an anti-message is sent after the response message to node 1, but is recognized only after node 1 uses the first response in a decision to claim bandwidth  $C$  bits per second bandwidth from the link LP, before the anti-message catches up with it (N.B., our understanding of GTW is that event processing routines are atomic, meaning that so long as the anti-message arrives *after* the initiation of the event that generates the bandwidth claim message, that erroneous message will be sent). Node 1's bandwidth claim is destined to be annihilated, because node 1 is destined to be rolled back to deal with the link LP's new (empty) state. But, the link LP processes the bandwidth claim from a state where no bandwidth is available. Of course, eventually the link LP will be rolled back when the bandwidth claim message is annihilated.

So why should we be concerned if an LP processes a funny looking message, since that will all get sorted out with rollbacks? We ought to be concerned because the code processing that message may not have been designed to deal with anomalous messages. We ought to be concerned because by combining the state of the message with the state of the LP it is conceivable that the LP code will do any one of a number of bad things, including

- indexing outside of array bounds to damage memory or cause a segmentation fault,
- call a recursive function with arguments that do not yield a “bottom” to the recursion,
- enter an infinite loop,
- commit some numerical error such as divide-by-zero, (under/over)-flow, negative arguments to an library routine expecting positive arguments,
- delete an object from an empty data structure,

- just about any bone-headed error you’ve ever done or ever seen done in a C or C++ program.

The point should be clear, the danger of processing an inconsistent message is that the code developer has a certain model of system behavior in mind that derives from physical reality. Processing of an inconsistent message can push the LP into an unforeseen state that does not correspond to physical reality. While the code may be safe and correct in all states corresponding to physical reality (the only states in which it will find itself in a correct serial simulation or a conservatively synchronized parallel simulation), it might not be safe in non-physical states. As it processes an inconsistent message it may behave in unforeseen ways, damaging memory in the runtime system or even in the parallel simulation libraries. Damaged memory that is not considered to be part of the Time Warp “state” is damaged forever, and has the potential to crash the simulation, alter the behavior of the simulation, or corrupt some data associated with the simulation.

### 3 Safety through Methodology

Once we understood the source of the problem we saw that we could try to detect when a message was inconsistent and not act upon it, or just allow inconsistent messages to make the LP link state nonsensical and try to prevent the simulator from damaging the runtime environment. We now explore these options. Both solution approaches rely on the LP code doing checking that may detect that the LP should be suspended until rolled back to an earlier time. We presume then that the Time Warp system includes a call to implement self-suspension.

To require that a code check the logical consistency of each message it processes is philosophically unsettling. We all learned at our mothers’ knees that Time Warp is supposed to make synchronization transparent to the user, it most definitely is not transparent if in order to ensure that it runs without crashing we must augment the code with extensive consistency checks. Granted, good software engineering practice calls for extensive checks; all you who routinely write code this way, please raise your hand. Hmm, I thought not. In any case, it may be technically difficult or even impossible to always determine whether a message is consistent. Asynchronous code is hard enough to develop correctly when one knows what the correct messages look like, let alone having to anticipate and protect against the potential of arbitrarily inconsistent messages.

The second approach would include the TWOS signal trapping trick, but would also try to detect problems before they occur. Arguments for all library functions would have to be tested for reasonableness, to avoid things like taking the logarithm of a negative number. Nearly every memory access has to be tested for reasonableness, even if pointers are banned. Every single read or write to an array must first check that the index is within the array bounds. This holds true even if the array is declared to be simulation “state”—its memory space is in the heap somewhere and stepping outside of its confines can cause damage. But it gets worse. Some array writes are done tacitly, using C/C++ library calls. One can imagine a string being created using **sprintf** but for that string to exceed the allocated space because the string contents depend on an inconsistent message. The ability for detecting memory access problems has gotten quite comprehensive, it is conceivable that most such problems could be caught using the sort of technology behind commercial

tools like Purify [11] and insure++ [2]. To develop that technology independently for a parallel simulation engine is a daunting task.

A “catch-it-in-the-act” approach will also have to deal with bottomless recursion and infinite loops. There is a serious theoretical problem here, in that the well-known halting problem asserts that there is no algorithm that can take an arbitrary loop and detect whether it terminates. Protection from infinite looping has to be ad-hoc. To be completely safe one would have to be able to detect when processing of a message could lead to an infinite loop or bottomless recursion, and this is definitely non-trivial.

In summary, to rely on user-supplied consistency checking alone to filter out inconsistent messages is to court disaster. On the other hand, the implementation cost of monitoring executing C/C++ code to protect the runtime system from all possible ways of being trashed is overwhelming. In either case, substantially more work is involved to ensure that the parallel simulation runs safely than is required for a serial or conservatively synchronized simulation. It is clearly not enough to test a parallel simulation on one processor and expect it to always run safely in parallel.

The only hope for a comprehensive solution is to ensure that each LP’s code is run in isolation and cannot damage the environment. At no time can the code be left to run on its own until “completion”, because “completion” may never come. These are actually the same issues behind running Java [5] applets safely; a truly comprehensive solution might be based on using Java to express and execute LP code, or use some other interpreted language. In the meantime, what can we do with the C/C++ based Time Warp systems?

## 4 Rollback Consistency and Stale States

A first step towards dealing with the consistency problem is to define our terms. The root cause of the problem in the multicast simulation was that a rollback or cancelation process occurred, but the LP reflected the post- (alternatively, pre-) rollback system state and the message reflected the pre- (alternatively, post-) rollback system state. This leads us to define rollback consistency.

One can think of Time Warp’s execution on an LP as defining a tree, branches occurring where rollbacks are induced. Each rollback creates a new arm that is followed, until a rollback splits it. This is illustrated in Figure 3 where a sequence of four time-lines shows the evolution of this tree. The extent of each arm denotes the distance in simulation time the LP advanced before being rolled back. The solid line denotes the current state evolution path, dotted lines denote “dead” paths. Labeled black boxes identify points where the LP generated a message; arrows identify points in simulation time where the LP is rolled back. A circle marks the branch in the tree caused by a rollback, and is labeled with the simulation time of the rollback.

One can imagine sampling the state of the LP at different points in execution time, each sample would map to the end of the currently “active” execution arm; e.g., one could sample the state at the point message *A* is sent, and again at the point message *B* is sent. At the instant the state was sampled, the active tree arm would be at the label *A* in the first case, and *B* in the second case. The execution tree gives us a way of reasoning about the consistency of LP state sampled at two



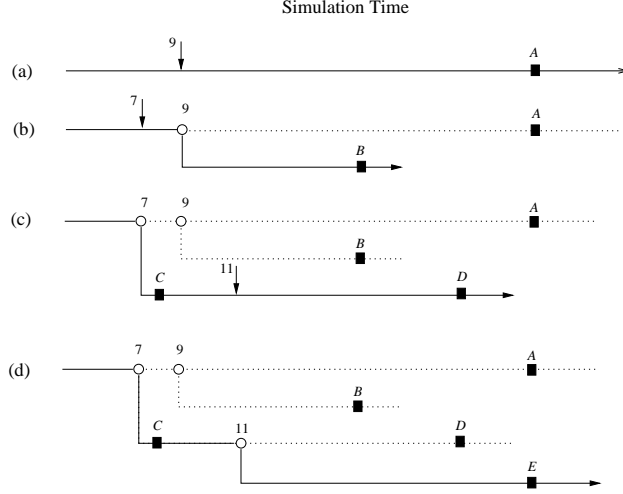


Figure 3: The evolution of an execution tree

different points in simulation (and real) time. We'll say that two samples are *rollback consistent* if they lie on a common path (including branches) in the execution tree. Samples associated with messages *C* and *D* are consistent (even after the rollback at time 11), as are samples associated with messages *C* and *E*. No other pair of labeled points are consistent. Given two consistent samples, we can order them by simulation time.

Next we think about how an LP's state evolves as a function of the states of other LPs at various points in simulation time. Conceptually, at any instant we could describe how the state of LP *i* has been influenced by all other LPs, in terms of the data state of all other LPs at the various last (in real time) times they affected LP *i*. We can track these dependencies, as follows. Associate with each LP *i* a dependency vector (DV) that contains a component for every LP. The  $j^{th}$  component holds a code describing the last state of LP *j* to affect LP *i*. Initially the DV has null components, save for the LP's own component; the DV is updated when an ordinary message is accepted, to reflect the new influences on the LP's state (anti-messages are excluded from this discussion). This is accomplished by associating with every message the sender's DV at the time of transmission. As the message is processed we update the recipient's DV by merging it with the message's DV. For each component we save the most "up-to-date" of the two. This way of thinking about dependency is basically Lamport's idea of distributed clocks [7].

Within this conceptual framework we can identify situations where inconsistencies arise. If for any component *j* the recipient's code for *j* is rollback-inconsistent with the message's component for *j*, then we know that LP *j* underwent a rollback that affected and is reflected in the state of either the sender or receiver, but not both. Returning to the time-line of Figure 2, we see that at the point that the link LP accepts the inconsistent message, the state of the link LP reflects the time 90 rollback, but that the link component for the message's DV does not reflect it. The link state component of the recipient is rollback-inconsistent with the link state component of the message.

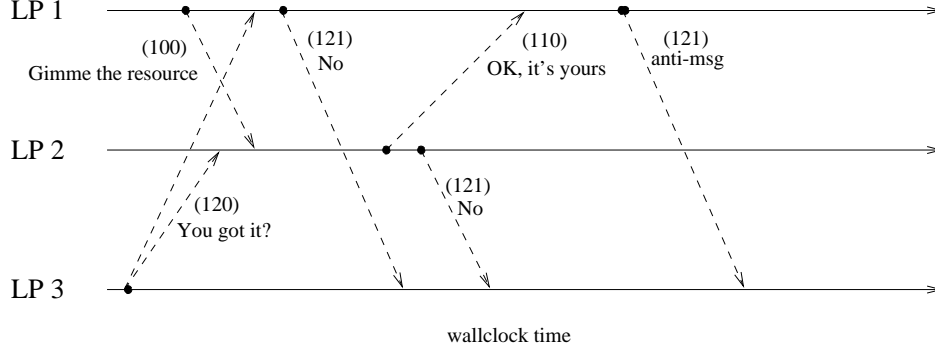


Figure 4: Inconsistency due to stale state.

A concrete example of a state code that detects rollback-inconsistency is a certain type of list. The first list element gives the simulation time of the sampled state. Following this is an ordered list of simulation times at which the LP was rolled back prior to sampling the state. Rollback times appear in this list in the order that the rollbacks were applied. For example, in Figure 3 the code for the LP state when message  $E$  is sent is the send-time of that message, followed by  $(9, 7, 11)$ . Let  $(t_1, L_1)$  and  $(t_2, L_2)$  two codes for an LP, where  $t_1$  and  $t_2$  are simulation times and  $L_1$  and  $L_2$  are ordered lists of rollback times. If these lists have different lengths, then the shorter list is necessarily a proper prefix of the longer, e.g., (without loss of generality)  $L_1 = (L_2, L'_1)$ . If there is any rollback time in  $L'_1$  that is less than  $t_2$ , the codes are rollback-inconsistent.  $(t_1, L_1)$  was sampled later in real-time than was  $(t_2, L_2)$ , and reflects a rollback that brought the LP behind the simulation time of  $(t_2, L_2)$ 's sample. If instead there is no rollback in  $L'_1$  with a time-stamp less than  $t_2$ , then the additional rollbacks reflected in  $L_1$  happen too late in simulation time to affect the sample at  $(t_2, L_2)$ , and so the codes are rollback-consistent.

However, there is another source of inconsistency, due instead to what we'll call "stale states". An simple 3 LP example illustrates this possibility. A time-line for the scenario is given in Figure 4. There is a resource that at any point in simulation time is held by either LP 1 or LP 2. The resource is held by an LP until the other requests it, and some random time after the request, the resource is released to the LP requesting it. Now imagine that at time 100 LP 2 has the resource and LP 1 requests it. LP 1 does not know when it will actually acquire the resource, and so continues optimistically on to an event at time 120, under the assumption that it does not have the resource at time 120. The event processed at time 120 responds to a query by LP 3, "Do you have the resource now?". Assuming not, LP 1 replies "No" at time 121. Sometime after this exchange LP 2 decides to yield the resource, at simulation time 110. Immediately after sending the "It's yours now" message to LP 1, it processes a query event from LP 3 at simulation time 121. "No", it replies. Upon receipt of this second negative response, LP 3 is in an illogical (with respect to the model semantics) state. We cannot pin this situation on a rollback inconsistency, because no rollbacks have yet occurred.

The problem in this case is that LP 3's state is "stale" with respect to the query response

message it receives from LP 2. It is stale in the sense that some action has been initiated that ultimately will roll LP 3 back, that the LP 2 data dependency component of LP 2's message to LP 3 is of a state that follows that initiation, but the LP 2 component of LP 3's data dependency vector will be affected by that initiation, but has not yet been affected by it.

More formally, if  $M$  is a message processed by LP  $j$ , we'll say that LP  $j$ 's state is stale with respect to  $M$  if  $M$ 's dependency vector component for some LP  $k$  reflects a state of LP  $k$  that follows its transmission of a message that initiates a rollback, the penultimate result of which is to rollback LP  $j$ , but which result has not yet occurred. The definition of  $M$  being stale with respect to LP  $j$ 's state is entirely similar, save that the penultimate result is that  $M$  is annihilated.

Rollback-inconsistency and stale state are related concepts in that rollback inconsistency occurs when a completed rollback makes two sampled states inconsistent, whereas stale state occurs when an initiated but as yet uncompleted rollback chain makes two sampled states inconsistent. For example, whereas states associated with  $C$  and  $D$  in Figure 3 are rollback consistent, once the first message responsible for initiating the rollback chain that causes the rollback at time 11 is sent, state  $D$  becomes stale, even before the time 11 rollback is recognized.

The problems of rollback inconsistency and stale state can be both eliminated by the simple mechanism of requiring message acknowledgments. The discussion below assumes the use of aggressive cancelation (also a modified lazy cancelation is possible so long as before a rolled back LP sends any new post-rollback message, all previously sent messages with larger time-stamps are aggressively canceled, with acknowledgments all received).

When an LP sends an ordinary message, it blocks from further processing until it receives an acknowledgment for that message (actually, all that is required is that it not send any new message before that acknowledgment is received). If a message (ordinary or anti-) is placed in LP  $j$ 's input buffer and does not cause rollback, that message is acknowledged immediately. If instead the message triggers a rollback, say at simulation time  $t$ , LP  $j$  does not acknowledge the message until it has itself received an acknowledgment for all anti-messages sent with time-stamps greater than  $t$ .

We must argue that this mechanism does not cause deadlock, and that it does indeed eliminate rollback inconsistency and stale data.

**Theorem 1** *Under message acknowledgments for anti-messages, and for ordinary messages, the system does not deadlock.*

**Proof:** For the sake of contradiction suppose the system is deadlocked. Among all blocked LPs, consider the source LP of the unacknowledged message with largest receive-time. We may assume that message is not in transit. Since the target has not acknowledged it, the message must have triggered a rollback that generated anti-messages, acknowledgments for which the target is still awaiting. But no such messages exist, because the target received the unacknowledged message with largest time-stamp. This establishes the contradiction and completes the proof.

□

The proof above does not depend on the type of message awaiting an acknowledgement, and so holds whether we acknowledge only anti-messages or all messages.

**Theorem 2** *Under message acknowledgments for anti-messages, rollback-inconsistency is eliminated.*

**Proof:** For the sake of contradiction, suppose a message  $M$  is delivered to LP  $k$  such that the message's dependency vector is rollback-inconsistent with LP  $k$ 's dependency vector in component  $j$ . Without loss of generality (and using the list code described earlier), suppose that LP  $k$ 's DV code for LP  $j$ ,  $(t_1, L_1)$ , is a later (with respect to wallclock time) reflection of LP  $j$ 's state than is the corresponding component  $(t_2, L_2)$  in  $M$ 's DV. Rollback-inconsistency implies that  $L_1 = (L_2, L'_1)$  for some non-empty list  $L'_1$ , and that  $L'_1$  contains some rollback time  $t_3$  with  $t_3 < t_2$ . We take  $t_3$  to be the first such rollback time in  $L'_1$ . Ultimately we can trace back the appearance of code  $(t_2, L_2)$  in  $M$ 's DV to a transmission at time  $t_2$  by LP  $j$ . When LP  $j$  processes the rollback at  $t_3$  after that transmission, it does not send any further messages before receiving an acknowledgment for the anti-message it sends to cancel the time  $t_2$  message. That anti-message, possibly triggering other anti-messages that must be acknowledged, erases all dependence of any LP on the state of LP  $j$  reported in the time  $t_2$  message. LP  $j$  cannot advance to any state represented by code  $(t_1, L_1)$  before that cancelation is complete. Hence, code  $(t_2, L_2)$  may not be associated with  $M$  if LP  $k$ 's code is  $(t_1, L_1)$ , establishing the contradiction and proving the theorem.

□

It is worth noting that a measure of safety can be gained just by acknowledging anti-messages. Additionally requiring acknowledgments for ordinary messages brings freedom from stale states as well.

**Theorem 3** *Under message acknowledgments for ordinary and anti-messages, the system is free from stale states.*

**Proof:** Suppose that LP  $k$ 's state is stale with respect to message  $M$  in the dependency vector component for LP  $j$ . This means that LP  $j$  sent some message  $M'$  before achieving the state reflected in  $M$ 's DV component for LP  $j$ , a message that triggers a rollback chain that will ultimately affect LP  $j$ , but has not. This cannot occur, as LP  $j$  awaits an acknowledgment for  $M'$  before sending any further messages. A similar argument shows that  $M$  cannot be stale with respect to LP  $j$ 's state.

□

Two important points should be noted here. First, Time Warp pioneers recognized that if the system contained messages that would cause an LP to rollback and messages that would cause it to move forward, then the rollback should have precedence. This could be done heuristically by always processing anti-messages before other messages. Some schemes even proposed preemptive rollbacks

of all LPs within some “distance” of a temporal error without bothering to see if anti-messages would indeed trigger rollbacks there [9]. Our acknowledgments are the logical extension of such thinking. Second, waiting for acknowledgments before allowing an LP to send another message need not impact performance greatly. This is a matter of latency hiding. If there are many LPs on each processor, then after suspending one we may well be able to find many that have useful work to perform while the first is blocked. In any case, the requirement is that an LP not send another message without appropriate acknowledgments, not that it cannot process. It is viable to allow the LP to continue executing, and buffer its messages until appropriate acknowledge releases are obtained.

However, it again is not difficult to see that even without rollback inconsistencies or stale state that an LP can be driven into a state that is at odds with actual model semantics. Consider now a three LP simulation of a control loop. LP 1 increments an 8-bit counter every  $d$  units of simulation. LP 3 can send LP 1 a message to adjust the inter-increment spacing  $d$  to some new value; LP 1 sends LP 3 a message whenever its counter crosses from value 63 to 64. LP 2 sends LP 1 a message, at random epochs, to clear the counter. Figure 5 illustrates the system. Control in this system is provided by LP 3. The logic of the underlying physical system is that the LP 1 counter never overflows, and that there are upper and lower bounds on the value of  $d$  that LP 3 may choose for LP 1. If for some reason LP 2 were to be slowed down in its execution, LP 1 can increment the counter to overflowing, and as a result provide non-physical behavior statistics to LP 3, in such a way that the constraints of the underlying control law are violated.

There are actually two sources of trouble in this example. One is that LP 1 sends risky messages to LP 3, befouling LP 3’s internal state. The other is that LP 1 proceeds aggressively beyond its own physical parameters, to overflow the counter. In the next section we examine the benefits of eliminating the first trouble source, and look at how to live with the second.

## 5 Safety and Risk-Free Protocols

In our view, the real danger of allowing risky messages is that in a complex code the space of possible nonsense states into which an LP might be driven is too large to anticipate. Intuition will guide a model developer so long as the LP data state can be assumed to reflect a real possible state in the modeled physical system. Even though banning risk *still* allows one to get into states that are inconsistent with model semantics, we argue that if the model code is safe under all “internally speculative” scenarios, then it is safe under a risk-free protocol.

Reconsider the control loop example from the last section, and imagine that it is simulated with a risk-free synchronization protocol. LP 1 may simulate accurately through some  $S$  units of simulation time that contains “increment” events, and risk-free “clear counter” events. But, to process beyond this interval is to process aggressively; it may do so without receipt of any “clear-counter” messages from LP 2 through enough simulation time to cause the counter to overflow. Under a risk-free protocol, LP 1 will withhold all messages it might generate for LP 3 until it can be certain that those messages are correct. So, while in this example LP 1 may wander into

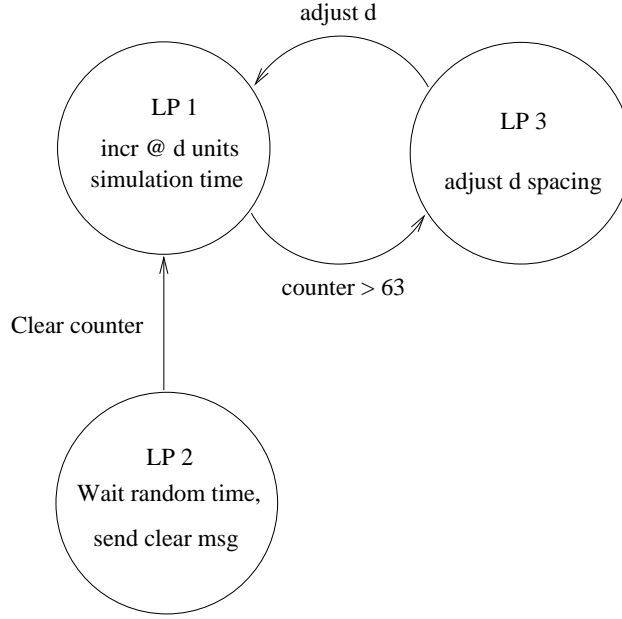


Figure 5: Control loop example illustrating that an LP may be driven into a non-physical state even in the absence of rollback inconsistencies and stale state.

non-physical states due to its own aggressive processing, LP 3 is not affected by the result of LP 1's aggression.

While inconsistency is still possible in LP 1, there is a critical difference, that the inconsistency derives solely from actions that are defined internally by LP 1. This constraint vastly simplifies the programmer's job in verifying the safety of the program. For, let  $\mathcal{S}$  denote the set of "real" LP data states, those corresponding to physical reality. During testing and verification of correctness, one ensures that the transitions between states in  $\mathcal{S}$  is correct in response to a set of *external* messages  $M_E$  and in response to a set of *internal* messages  $M_I$ . If a risk-free protocol is used, to test or verify safety, one needs only to ensure that the LP is safe within all states  $\mathcal{S}' \supseteq \mathcal{S}$ , obtained by considering all ways of starting with a state in  $\mathcal{S}$  and repeatedly making transitions by accepting messages from  $M_I$ . Contrast this with the need to test or verify the set of states  $\mathcal{S}'' \supseteq \mathcal{S}'$ , obtained by considering all ways of starting with a state in  $\mathcal{S}$  and repeatedly making transitions driven by messages of any kind or content. In the former case it is reasonable to expect the code developer to have intuition about the behavior of the LP code in  $\mathcal{S}'$ , in the latter case it is a much harder job.

## 6 Ramifications

If one is to take our warnings seriously, what are the ramifications for doing optimistic parallel discrete-event simulation within a Unix C/C++ environment ? There are ramifications for the simulator, and ramifications for user code, issues we treat separately.

## 6.1 Ramifications for Parallel Simulator

Accepting the premise that complete protection from inconsistency and its consequences cannot be provided automatically, we will rely on the user to provide error checking. To support this the simulator should provide a procedure call, say, **SuspendLP(int LPid, char\* ErrMsg)**, to suspend an LP from further processing until it is rolled back. An error message provided with that call as an argument is printed if the GVT advances past the LP's simulation time when suspended. Careful users may embed consistency checks within their code and call **SuspendLP** upon evidence of logical inconsistency.

The simulator should protect itself against UNIX error signals, as did TWOS. This is accomplished simply by (i) having the simulator call the Unix function **signal** for each of the error signals to trap, informing Unix of the signal trap to call upon its occurrence; (ii) having the simulator call the Unix **setjmp** function once within the scheduler to save a snapshot of the process context, (iii) handle trapped errors by calling **SuspendLP**, and return control to the scheduler loop using the Unix **longjmp** function.

With effort, some protection against a blown stack may be provided if the simulator includes a call allowing the user to specify a maximum user code call stack depth (in number of calls) and/or maximum stack depth (in number of bytes). That's the easy part. The harder part is to write code that modifies the user code binary, checking the stack for consistency with these declared constraints. This might be done using a tool such as EEL [8], which can be taught how to recognize object code that is setting up a procedure call, and can then insert additional consistency checking code. Such a solution is highly dependent on the underlying hardware.

The simulator ought to provide an option for risk-free operation.

A C++-based simulator should provide base classes for array types that throw exceptions when an access is attempted that falls outside of the array bounds. The exception handler should call **SuspendLP**.

The simulator may provide a final measure of insurance by eliminating rollback-inconsistencies, and stale states as we have described. Despite all these precautions, participation by the user is required, described next.

## 6.2 Ramifications for User Code

While the parallel simulator can catch some problems resulting from inconsistencies, it cannot catch all of them. The user has to be responsible for ensuring that no memory write is harmful, and that control is not lost to an infinite loop or bottomless recursion. The user's burden is very large; in C/C++ there are a multitude of ways to trash memory. Every one has to be anticipated and tested for. Equally weighty is the responsibility to detect when control is lost to an infinite loop or endless recursion. All we can do is provide the simulator with the features described earlier, and provide the user with strong remonstrations to do consistency checking and use those features, especially with regards to memory referencing, loops, and calling behavior.

Until LP code is run in isolation, the only complete way to be assured that inconsistent pro-

cessing does not harm the simulation is to prove this, formally. Failing that, we can only trust to providence that the simulation is safe and is behaving as it should. While this sounds bleak, in truth, even after extensive testing and debugging only providence is trusted for ordinary complex software systems that control nuclear power plants, fly airplanes, and route trains.

## 7 Conclusions

We remind the community that optimistic processing implies that LPs may be temporarily driven into nonintuitive states. We point out that with current trends in using C and C++ as the basis for parallel simulation, this creates a danger of damaging the simulation while it executes in one of these states, for the executing code has access to portions of the stack, heap, and static data areas that are not checkpointed.

Our concern is that parallel simulation is on the threshold of being used to build large complex models, but that the safety ramifications of optimistic processing in general, and risky messages in particular are not well understood by those who would build those simulators. For, the model code has to be resilient enough not to crash the system, even when pushed into transient, but unexpected non-physical non-intuitive states.

We argue that the only comprehensive solution is to isolate an LP's execution from everything else, which could be accomplished by interpreting LP code rather than executing it; however, this solution is not realistic for current C/C++ based simulators and so we consider what might be done for them.

We observe that lagging rollbacks and stale states are two important causes of an LP entering a nonsense state, and show that requiring acknowledgments from anti-messages eliminates lagging rollbacks, and that additionally requiring acknowledgments from ordinary messages eliminates stale states. We then observe that the possibility for an LP to enter a nonsense state remains.

We note that the problem of verifying an LP code's safety is much reduced if it can be assumed that a risk-free synchronization protocol will be used. The programmer needs only consider the effects of speculative computation that are entirely internal to the LP. This eliminates the need to anticipate against processing arbitrarily illogical messages. Finally, we summarize with a list of ramifications our warnings may have on parallel simulators and parallel simulation user code.

Optimistic synchronization provides the only way some important problem classes can be simulated with fidelity on parallel machines. However, it is important to realize that the software engineering burden of using Time Warp is higher than for serial simulation. So long as the LP code can adversely affect its operating environment, synchronization concerns are **not** transparent to the modeler. There are some things that can be done automatically to reduce the threat, but they do not come for free. The acknowledgments we propose may impact performance, but will reduce the number of ways of triggering an inadvertent crash. Use of a risk-free protocol may impact performance, but may make it feasible to have confidence that the simulation will run safely in parallel. These are tradeoffs that have to be considered, and which have not been emphasized until now.



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