and there is nothing else we can do. However, if there are other copies of $A$, then we can proceed as if the copy at $N$ did not exist. When $N$ recovers, it not only has the responsibility to find out about the transactions being committed or aborted when it failed, but now it must find out which of its items are out of date, in the sense that transactions have run at the other sites and modified copies of items that, like $A$, are found at $N$ and also at other nodes.

### Obtaining Up-to-Date Values

When the failed site resumes activity, it must obtain the most recent values for all its items. We shall suggest two general strategies for doing so.

1. If site $M$ discovers that site $N$ has failed, $M$ records this fact in its log. When $N$ recovers, it sends a message to each site. If $M$ receives such a message, $M$ examines its log back to the point where it discovered $N$ had failed, and sends the most recent value it has for all items it holds in common with $N$.[15] The values of these items must be locked while the recovery of $N$ is in progress, and we must be careful to obtain the most recent value among all of the sites with copies. We can tell the most recent values, because all transactions that have committed a value for item $A$ must have done so in the same order at all the sites of $A$, provided we have a correct locking method. If we are using timestamp-based concurrency control, the write-times of the values determine their order.
2. All copies of all items may be assigned a write-time, whether or not timestamp concurrency control is in use. When a site $N$ recovers, it sends for the write-times of all its items, as recorded in the other sites. These items are temporarily locked at the other sites, and the current values of items with a more recent write-time than the write-time at $N$ are sent to $N$.

This description merely scratches the surface of the subject of crash management. For example, we must consider what happens when a site needed to restore values to a second site has itself failed, or if a site fails while another is recovering. The interested reader is encouraged to consult the bibliographic notes for analyses of the subject.

## 10.8 DISTRIBUTED DEADLOCKS

Recall from Section 9.1 that we have simple and elegant methods to prevent deadlock in single-processor systems. For example, we can require each transaction to request locks on items in lexicographic order of the items' names. Then it will not be possible that we have transaction $T_1$ waiting for item $A_1$ held by

[15] Note that under the methods of locking and commitment described in this chapter, $M$ must discover $N$ has failed if there is a transaction that involves any item held by both $N$ and $M$, so $N$ will hear of all its out-of-date items.



$T_2$, which is waiting for $A_2$ held by $T_3$, and so on, while $T_k$ is waiting for $A_k$ held by $T_1$. That follows because the fact that $T_2$ holds a lock on $A_1$ while it is waiting for $A_2$ tells us $A_1 < A_2$ in lexicographic order. Similarly, we may conclude $A_2 < A_3 \cdots A_k < A_1$, which implies a cycle in the lexicographic order, an impossibility.

With care, we can generalize this technique to work for distributed databases. If the locking method used is a centralized one, where individual items, rather than copies, are locked, then no modification is needed. If we use a locking method like the $k$-of-$n$ schemes, which lock individual copies, we can still avoid deadlocks if we require all transactions to lock copies in a particular order:

1. If $A < B$ in lexicographic order, then a transaction $T$ must lock all the copies of $A$ that it needs before locking any copies of $B$.
2. The copies of each item $A$ are ordered, and a transaction locks all copies of $A$ that it needs in that order.

Even if it is possible under some circumstances to avoid deadlock by judicious ordering of copies, there is a reason to look elsewhere for a method of dealing with deadlocks. We discussed in Example 9.21 why it is sometimes difficult to predict in advance the set of items that a given transaction needs to lock. If so, then locking needed items in lexicographic order is either not possible or requires the unnecessary locking of items.

In the remainder of this section we shall take a brief look at some general methods for deadlock detection and deadlock avoidance that do not place constraints on the order in which a transaction can access items. First, we consider the use of timeouts to detect and resolve deadlocks. Next, the construction of a waits-for graph is considered as a detection mechanism. Finally, we consider a timestamp-based approach to avoiding deadlocks altogether.

### Deadlock Resolution by Timeout

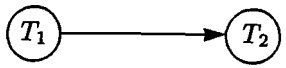
A simple approach to detecting deadlocks is to have a transaction time out and abort if it has waited sufficiently long for a lock that it is likely to be involved in a deadlock. The timeout period must be sufficiently short that deadlocked transactions do not hold locks too long, yet it must be sufficiently long that we do not often abort transactions that are not really deadlocked.

This method has a number of advantages. Unlike the waits-for-graph approach to be described next, it requires no extra message traffic. Unlike the timestamp-based methods to be described, it does not (usually) abort transactions that are not involved in a deadlock. It is prone, however, to aborting all or many of the transactions in a deadlock, rather than one transaction, which is generally sufficient to break the deadlock.

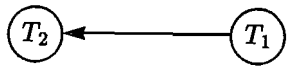
### Waits-for-Graphs

We mentioned in Section 9.1 that a necessary and sufficient test for a deadlock in a single-processor system is to construct a *waits-for graph*, whose nodes are the transactions. The graph has an arc from $T_1$ to $T_2$ if $T_1$ is waiting for a lock on an item held by $T_2$. Then there is a deadlock if and only if there is a cycle in this graph. In principle, the same technique works in a distributed environment. The trouble is that at each site we can maintain easily only a *local* waits-for graph, while cycles may appear only in the *global* waits-for graph, composed of the union of the local waits-for graphs.

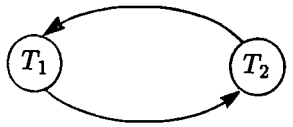
**Example 10.7:** Suppose we have transactions $T_1$ and $T_2$ that wish to lock items $A$ and $B$, located at nodes $N_A$ and $N_B$, respectively. $A$ and $B$ may be copies of the same item or may be different items. Also suppose that at $N_A$, (a subtransaction of) $T_2$ has obtained a write-lock on $A$, and (a subtransaction of) $T_1$ is waiting for that lock. Symmetrically, at $N_B$ $T_1$ has a lock on $B$, which $T_2$ is waiting for.




(a) Local waits-for graph at $N_A$.




(b) Local waits-for graph at $N_B$.




(c) Global waits-for graph.

**Figure 10.7** Global deadlock detection.

The local waits-for graphs at $N_A$ and $N_B$ are shown in Figure 10.7(a) and (b); clearly each is acyclic. However, the union of these graphs is the cycle shown in Figure 10.7(c). As far as we can tell at either of the sites $N_A$ or $N_B$, there might not be a deadlock. For example, from $N_A$ alone, we cannot be sure that anything prevents $T_2$ from eventually committing and releasing its lock on $A$, then allowing $T_1$ to get the lock. □

Example 10.7 illustrates why in order to detect cycles it is necessary to send messages that allow a global waits-for graph to be constructed. There are several ways this task could be accomplished:



1. Use a central node to receive updates to the local waits-for graphs from all of the sites periodically. This technique has the advantages and disadvantages of centralized methods of locking: it is vulnerable to failure of the central node and to concentration of message traffic at that site,[16] but the total amount of traffic generated is relatively low.
2. Pass the current local waits-for graphs among all of the sites, preferring to append the local graph to another message headed for another site if possible, but sending the local graph to each other site periodically anyway. The amount of traffic this method generates can be much larger than for the central-node method. However, if the cost of messages is relatively invariant to their length, and frequently waits-for information can be "piggybacked" on other messages, then the real cost of passing information is small.

### Timeliness of Waits-for Graphs

In either method described above, the union of the local waits-for graphs that any particular site knows about currently does not have to reflect the situation that existed globally at any particular time. That doesn't prevent the detection of deadlocks, since if a cycle in the global waits-for graph exists, it won't go away until the deadlock is resolved by aborting at least one of the transactions involved in the cycle. Thus, the arcs of a cycle in the global graph will eventually all reach the central node (in method 1) or reach some node (in method 2), and the deadlock will be detected.

However, errors in the opposite direction can occur. There can be *phantom* deadlocks which appear as cycles in the union of the local waits-for graphs that have accumulated at some site, yet at no time did the global waits-for graph have this cycle.

**Example 10.8:** The transaction $T_2$ in Example 10.7 might decide to abort for one of several reasons, shortly after the local graph of Figure 10.7(a) was sent to the central site. Then the graph of Figure 10.7(b) might be sent to the central site. Before an update to Figure 10.7(a) can reach the central site, that node constructs the graph of Figure 10.7(c). Thus, it appears that there is a deadlock, and the central node will select a victim to abort. If it selects $T_2$, there is no harm, since $T_2$ aborted anyway. However, it could just as well select $T_1$, which would waste resources. □

### Timestamp-Based Deadlock Prevention

We mentioned schemes that avoid deadlocks by controlling the order in which

[16] Note that in comparison, centralized, or coordinator-based distributed commit protocols

items are locked by any given transaction, e.g., locking in lexicographic order or taking all locks at once. There also are schemes that do not place constraints on the order in which items are locked or accessed, but still can assure no deadlocks occur. These schemes use timestamps on transactions, and each guarantees that no cycles can occur in the global waits-for graph. It is important to note that the timestamps are used for deadlock avoidance only; access control of items is still by locking.

In one scheme, should (a subtransaction of) $T_1$ be waiting for (a subtransaction of) $T_2$, then it must be that the timestamp of $T_1$ is less than the timestamp of $T_2$; in the second scheme, the opposite is true. In either scheme, a cycle in the waits-for graph would consist of transactions with monotonically increasing or monotonically decreasing timestamps, as we went around the cycle. Neither is possible, since when we go around the cycle we come back to the same timestamp that we started with.

We now define the two deadlock avoidance schemes. Suppose we have transactions $T_1$ and $T_2$ with timestamps $t_1$ and $t_2$, respectively, and a subtransaction of $T_1$ attempts to access an item $A$ locked by a subtransaction of $T_2$.

1. In the *wait-die* scheme, $T_1$ waits for a lock on $A$ if $t_1 < t_2$, i.e., if $T_1$ is the older transaction. If $t_1 > t_2$, then $T_1$ is aborted.
2. In the *wound-wait* scheme, $T_1$ waits for a lock on $A$ if $t_1 > t_2$. If $t_1 < t_2$, then $T_2$ is forced to abort and release its lock on $A$ to $T_1$.[17]

In either scheme, the aborted transaction must initiate again with the same timestamp, not with a new timestamp. Reusing the original timestamp guarantees that the oldest transaction, in either scheme, cannot die or be wounded. Thus, each transaction will eventually be allowed to complete, as the following theorem shows.

**Theorem 10.3:** There can be neither deadlocks nor livelocks in the wait-die or the wound-wait schemes.

**Proof:** Consider the wait-die scheme. Suppose there is a cycle in the global waits-for graph, i.e., a sequence of transactions $T_1, \ldots, T_k$ such that each $T_i$ is waiting for release of a lock by $T_{i+1}$, for $1 \leq i < k$, and $T_k$ is waiting for $T_1$. Let $t_i$ be the timestamp of $T_i$. Then $t_1 < t_2 < \cdots < t_k < t_1$, which implies $t_1 < t_1$, an impossibility. Similarly, in the wound-wait scheme, such a cycle would imply $t_1 > t_2 > \cdots > t_k > t_1$, which is also impossible.

To see why no livelocks occur, let us again consider the wait-die scheme. If

[17] Incidentally, the term "wound-wait" rather than "kill-wait" is used because of the image that the "wounded" subtransaction must, before it dies, run around informing all the other subtransactions of its transaction that they too must abort. That is not really necessary if a distributed commit algorithm is used, but the subject is gruesome, and the less said the better.



| Method | Messages | Phantom aborts | Other |
|---|---|---|---|
| Timeout | None | Medium number | Can abort more than one transaction to resolve one deadlock |
| Waits-for Graph Centralized | Medium traffic | Few | Vulnerable to node failure, bottlenecks |
| Waits-for Graph Distributed | High traffic | Few | |
| Timestamp | None | Many | |

**Figure 10.8** Comparison of deadlock-handling methods.

$T$ is the transaction with the lowest timestamp, that is, $T$ is the oldest transaction that has not completed, then $T$ never dies. It may wait for younger transactions to release their locks, but since there are no deadlocks, those locks will eventually be released, and $T$ will eventually complete. When $T$ first initiates, there are some finite number of live, older transactions. By the argument above, each will eventually complete, making $T$ the oldest. At that point, $T$ is sure to complete the next time it is restarted. Of course, in ordinary operation, transactions will not necessarily complete in the order of their age, and in fact most will proceed without having to abort.

The no-livelock argument for the wound-wait scheme is similar. Here, the oldest transaction does not even have to wait for others to release locks; it takes the locks it needs and wounds the transactions holding them. □

### Comparison of Methods

Figure 10.8 summarizes the advantages and disadvantages of the methods we have covered in this section. The column labeled "Messages" refers to the message traffic needed to detect deadlocks. The column "Phantom aborts" refers to the possibility that transactions not involved in a deadlock will be required to abort.