Pronto: High Availability for Standard Off-the-shelf Databases*

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Abstract

Enterprise applications typically store their state in databases. If a database fails, the application is unavailable while the database recovers. Database recovery is time consuming because it involves replaying the persistent transaction log. To isolate end-users from database failures we introduce Pronto, a protocol to orchestrate the transaction processing by multiple, standard databases so that they collectively implement the illusion of a single, highly-available database. Pronto is a novel replication protocol that handles non-determinism without relying on perfect failure detection, does not require any modifications in existing applications and databases, and allows databases from different providers to be part of the replicated compound.

Index terms: database replication, failover, heterogeneous databases, primary-backup, atomic broadcast

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1 Introduction

High availability is essential for mission-critical computing systems. This is especially true for Internet-based e-commerce applications: if the application is unavailable, the business is closed. Such applications commonly follow a three-tier structure, where front-end web browsers send http requests to middle-tier web servers, which perform transactions against a back-end database. As for most online transaction processing systems, the database is the availability bottleneck in three-tier applications. This is not surprising because the database usually contains the entire application state. In contrast, web servers are typically stateless. If a web server fails, browsers can failover to another web server and immediately continue their processing. Rebinding to another web server is usually orders of magnitude faster than recovering a database from a failure. Thus, one way to reduce the impact of database failures on the overall system downtime and to increase the availability of the three-tier application is to use multiple replicated databases in the back-end.

This paper presents Pronto, a protocol that orchestrates the execution of replicated databases. Pronto uses standard, off-the-shelf, and possibly heterogeneous, database systems for the back-end transaction processing. Moreover, Pronto guarantees strong consistency (i.e., one-copy serializability [8]), providing to the clients the illusion that the database ensemble is a single, highly-available database system. Being highly available means that users of the ensemble never wait for database recovery, even if individual databases in the ensemble fail.

Pronto supports "interactive" transactions whose structure and SQL statements are not known up front. This allows Pronto to be deployed as a special implementation of a standard transaction interface, such as JDBC [45]. With JDBC, transactions may be constructed incrementally, passing only a single SQL statement through the interface at a time. Deploying Pronto as a special implementation of JDBC means that neither the databases nor the application requires changes—we can force the application to load the Pronto JDBC driver instead of the standard JDBC driver by simply changing the CLASSPATH variable.

Database replication has been the subject of much research in the past years and many protocols have been proposed. Gray et al. [19] have classified database replication into

eager and *lazy*. Eager replication, the category Pronto falls into, ensures strong consistency. Lazy replication increases performance by allowing replicas to diverge, possibly exposing clients to inconsistent states of the database. Eager replication can be based on the *update everywhere* or on the *primary-backup* approach [19]. Update everywhere allows any copy of the database to be updated. Primary-backup assigns a single database, the primary, to process transactions and checkpoint its state to one or more backups. The backups will simply reproduce the primary's state by locally applying the shipped state. Usually, the actual information shipped to the backups is not the new database state but the transaction log [20].

Early work on eager update everywhere has been based on the read-one/write-all approach [8] and on quorum systems (e.g., [1, 2, 18, 30, 44]). More recently, several works have proposed implementing eager update everywhere replication using an underlying total order broadcast abstraction (e.g., [4, 21, 23, 34, 46]). In general, these protocols capture different trade-offs between scalability (in terms of throughput) of the replicated database system, underlying network assumptions, generality of the transaction model, and use of standard or custom databases. For example, some protocols have been optimized for wide-area networks [6, 40], while others exploit special local-area network properties [31]. The approach in [24] is to modify the underlying databases so that all write locks for a transaction can be acquired in a single atomic step. Compared to these existing approaches, Pronto uses standard databases and supports interactive transactions, whose structure is determined dynamically (i.e., the result of a previous query may determine which requests to execute subsequently).

Primary-backup replication can be configured as *1-safe* or *2-safe* [15, 20]. With a 1-safe configuration, the primary commits the transaction locally and then sends the transaction log to the backups. With a 2-safe configuration, the primary ships the transaction log to the backups and an atomic commit is used to ensure that either all databases will commit the transaction or none of them will. While 1-safe may result in lost transactions if the primary fails after committing the transaction locally and before sending the transaction log to the backups [20], 2-safe prevents the primary from committing a transaction before it is safely received at the backups [36] or the primary reliably detects the failure of the backups. Comparatively, Pronto prevents lost transactions and allows incorrect failure

suspicions.

Disaster recovery in a system consisting of a group of primary sites executing distributed transactions is discussed in [17]. Backup sites duplicate the database stored in the primary sites. Each primary site sends its transaction log to its corresponding backup site (or sites, if more than one backup exists). For performance reasons, the algorithm used is 1-safe. Even though update transactions are required to execute at primary sites, overall system performance can be improved by executing read-only queries at backup sites [37]. The authors have concluded that although a 1-safe mechanism reduces processing and communication significantly, a 2-safe approach may be preferable if transactions cannot be lost or if communication and processing are fast and lock contention is not serious [36].

Lazy replication usually leads to weak consistency models [38, 26] and has to deal with issues not related to Pronto replication model, such as data *freshness*, i.e., how often the primary should propagate updates to the backups and how often the backups should process these updates [33]. For example, in [48] a real-time primary-backup replication scheme which enforces temporal consistency among replicated servers is considered. Although the work does not address databases explicitly, one could possibly apply the ideas in the context of databases. To detect failures, the primary and the backups permanently exchange ping messages. After the detection of a failure, the backup simply starts a backup version of the application and uploads the current state information. The authors have found that "in general, the total detection and recovery time is dominated by the detection time."

Database replication has also been implemented using epidemic techniques. The idea is that updates pass through the system like an infectious disease, from site to site [14]. Although the approach is particularly suited for weak consistency [39], some epidemic protocols have been augmented to ensure serializability [3]. Ensuring serializability with lazy propagation has also been achieved by restricting the placement of replicas [9, 13] and building global replication graphs [10].

Commercial products (e.g., [32, 47]) have traditionally favored failover based on storage systems that are shared among the cluster nodes (e.g., a disk array), whereas Pronto does not assume a shared storage system among the replicas. Besides, lazy replication has

been provided by virtually every major commercial database, usually targeting at on-line analytical processing [43].

Pronto is a hybrid between primary-backup replication [11] and active replication [27, 42],[1] similarly to the leader-follower approach [7], developed in the context of real-time systems. Essentially, Pronto deals with database non-determinism by having a single (primary) database execute transactions in a non-deterministic manner. Rather than checkpoint the resulting state to backups, the primary sends the transaction itself to the backups along with ordering information that allows the backups to make the same non-deterministic choices as the primary. Like active replication, every database processes all transactions. Unlike traditional active replication, the backups process transactions after the primary, which allows the primary to make non-deterministic choices and export those choices to the backups. By shipping transactions instead of transaction logs, Pronto can support heterogeneous databases with different log formats, and prevent the contamination that may result if the data in one database becomes corrupt.

Primary-backup techniques usually rely on *failure detectors* (i.e., timeout mechanisms) to trigger the election of a new primary when the current one fails [8]. Setting the right timeout value is not straightforward, however. While fast failure detection is crucial for high availability—the longer it takes for the failure of the primary to be detected, the smaller the availability of the system—being too aggressive may result in false detections and multiple primaries executing simultaneously, which may compromise consistency. Pronto's solution to this problem is to allow the existence of several primaries during certain transitory conditions without leading to database inconsistencies. With Pronto, timeout mechanisms can be tuned to aggressively detect primary failures, without incurring inconsistencies due to false failures suspicions.

A remark is now in order considering Pronto's approach. Pronto was not designed to "compete" in performance with proprietary solutions. Even though the overhead introduced by Pronto is "acceptable"—experiments conducted with an ensemble of commercial databases, using a Java prototype interfaced through JDBC, have shown that when com-

[1] Active replication is a technique according to which replicas receive and execute all requests in the same total order. If the execution is deterministic, after having executed the same sequence of operations, every replica will reach the same local state [27, 42].

pared to a single-database configuration the overhead introduced by Pronto is below 20% in throughput and below 26% in response time—access to database internals allows optimizations not possible in a middleware protocol. On the other hand, Pronto is reasonably simple, can be readily put to use with off-the-shelf databases, and addresses the very practical problem of failure detection tuning.

The remainder of the paper is structured as follows. Section 2 describes the system model and some abstractions used in the paper, and formally states the problem we are concerned about. Section 3 presents the Pronto protocol in detail and discusses some additional aspects about Pronto. Section 4 describes our Pronto prototype, the experiments we conducted with it, and the results found. Section 5 concludes the paper. Proofs of correctness are presented in the Appendix.

2 Model, Definitions and Problem

2.1 Processes, Communication and Failures

We assume an asynchronous system composed of two disjoint sets of processes: a set $C = \{c_1, c_2, ...\}$ of database client processes (i.e., middle-tier web servers), and a set $S = \{s_1, s_2, ..., s_n\}$ of database server processes (i.e., back-end databases). Every database server has a copy of all data items. Processes can only fail by crashing (e.g., we do not consider Byzantine failures). For simplicity, database recovery is not introduced in the model, and treated later in the paper (see Section 3.4). We further assume that database clients and servers have access to failure detectors [12], used to monitor database server processes. The class of failure detectors we consider guarantees that every database server process that crashes is eventually suspected to have crashed *(completeness)*, and there is a time after which some database server process that does not crash is never suspected *(accuracy)* [12].

Processes are all connected through reliable channels, which neither lose nor duplicate messages. We do not exclude link failures, as long as we can assume that any link failure is eventually repaired. In practice, the abstraction of reliable channels is implemented by retransmitting messages and tracking duplicates. Reliable channels are defined by

the primitives *send*(m) and *receive*(m). Database server processes can also exchange messages using a broadcast abstraction built on top of reliable channels (also known as Atomic Broadcast or Total Order Broadcast). Broadcast communication is defined by the primitives *broadcast*(m) and *deliver*(m), and guarantees that if a database server process delivers a message m, then all database server processes that do not crash eventually deliver m *(agreement)*, and if two database servers, s_i and s_j, both deliver messages m_1 and m_2, then they do so in the same order *(total order)*.

2.2 Databases and Transactions

Databases are specified by a set of primitives and their associated behavior. The syntax and semantics of our database primitives are those of standard off-the-shelf relational database systems. We define transactions as sequences of database requests.

A database is an abstraction implemented by database server processes. The database abstraction is defined by the primitives presented next.

- `begin`(t_a) and `response`($t_a, -$). The `begin` primitive starts a transaction t_a in the database. It has to precede any other operations requested on behalf of t_a. The database issues a response once it is ready to process t_a's requests.

- `exec`(t_a, *`sql-st`*) and `response`(t_a, *`result`*). The `exec` primitive requests the execution of an SQL statement to the database. *`sql-st`* can be any SQL statement, except for commit and abort (e.g., select or update). The result can be the values returned from *`sql-st`* or an abort notification if t_a was involved in a deadlock, for example.

- `commit`(t_a) and `response`(t_a, *`result`*). The `commit` primitive terminates a sequence of `exec`'s for transaction t_a and requests t_a's commit. The response returns a confirmation that t_a has been committed or an abort notification.

- `abort`(t_a). The `abort` primitive terminates a sequence of requests for transaction t_a and requests t_a's abort. We assume that an abort request can always be executed, and so, there is no need for a confirmation response from the server.

We define a transaction t_a as a finite sequence $\langle \texttt{begin}(t_a); \texttt{response}(t_a, -); \texttt{exec}(t_a, -); \texttt{response}(t_a, -); ...; [\texttt{commit}(t_a); \texttt{response}(t_a, -) \ / \texttt{abort}(t_a)] \rangle$, where $\texttt{commit}(t_a)$; $\texttt{response}(t_a, -)$ and $\texttt{abort}(t_a)$ are mutually exclusive, although one must take place. Our definition of a transaction differs from traditional definitions (e.g., [8]) in that we focus on the requests submitted to the database and not on the operations performed by the database on the data items. For example, in some cases, even if a commit is requested for some transaction t_a, the database may decide to abort t_a.

A database server process s_i guarantees the following properties:

DB-1 Transactions are serialized by s_i using strict two-phase locking (strict 2PL).

DB-2 If a transaction is continously re-submitted, it is eventually commited.

DB-3 No transaction remains pending forever.

Property DB-1 ensures *serializability*, that is, any concurrent transaction execution $\mathcal{E}$ has the same effect on the database as some serial execution $\mathcal{E}_s$ of the same transactions in $\mathcal{E}$. Furthermore, strict 2PL schedulers have the following property, exploited by our protocol: if transaction t_a has been committed before transaction t_b by s_i in some execution $\mathcal{E}$, and t_a and t_b conflict,[2] then in every serial execution $\mathcal{E}_s$ equivalent to $\mathcal{E}$, t_a precedes t_b [8].

Property DB-2, although not explicitly stated as such, is often assumed to be satisfied by current database systems. DB-2 reflects the fact that even though in general, databases do not guarantee that a submitted transaction will commit (e.g., the transaction may get involved in a deadlock and have to be aborted), this does not mean that no liveness guarantee is provided.

Property DB-3 ensures that transactions terminate, either by committing, i.e., making their changes permanent to the database, or aborting, i.e., rolling them back. Thus, if a transaction cannot make progress because it is deadlocked or the client submitting the transaction's operations has crashed, the transaction will be eventually aborted by the database (and all its locks will be removed).

[2]Transactions t_a and t_b conflict if they both access a common data item and at least one of them modifies the data item.

2.3 Clients and Transactional-Jobs

The transactional-job abstraction models the business logic that runs in middle-tier web servers. The execution of a job generates a transaction that will be executed by database server processes. A job j terminates successfully if the transaction it generates requests a commit and is committed, or requests an abort.

The execution of a transactional job (or simply job, for short) is defined by the primitives `submit`(j) and `response`(*result*). The `submit`(j) primitive requests the execution of a job, and the `response`(*result*) primitive returns the results of the job.

Pronto uses the transactional-job abstraction to allow clients to access a replicated database as if they were accessing a highly-available single-copy database. It satisfies the following properties.

RDB-1 If $\mathcal{E}$ is an execution of the replicated database system, then there exists some serial execution $\mathcal{E}_s$ that is equivalent to $\mathcal{E}$.

RDB-2 If a client submits a transactional job j, and does not crash, then the client will eventually receive a response with the results of j.

RDB-1 is the serializability property in the context of replicated databases (also called one-copy-serializability). RDB-2 states that the submission of a job should always result in its successful execution against the database system.

3 The Pronto Failover Protocol

3.1 The Protocol at a Glance

The protocol is based on the primary-backup replication model, where one database server, the *primary*, is assigned a special role. The primary is the only server supposed to interact with the clients, who submit transaction requests resulting from the execution of a job. The other database servers (the *backups*) interact only with the primary.

Failure/Suspicion Free Execution. To execute a transactional job j, a client c takes the first transaction request originated from the execution of j (i.e., begin transaction)

and sends this request to the database server s that c believes to be, most likely, the current primary. After sending the begin transaction request, c waits for the result or suspects s to have crashed. The execution proceeds as follows (see Figure 1).

(a) If s is the current primary, it executes the request and sends the result to c. In this case, c continues the execution of j, by submitting other transaction requests to the primary on behalf of j. If the primary does not crash and is not suspected by c, the execution proceeds until c requests the transaction termination (see below).

(b) If s is not the current primary, it returns an error message to c, which will choose another database server s' and send to s' the transaction request.

(c) The case where c suspects s to have crashed is treated later in the section.

If the primary does not crash and is not suspected, the client eventually issues a request to terminate the transaction (i.e., commit or abort). The primary executes a commit request from the client by broadcasting the transaction unique identification, the SQL statements associated with the transaction, and some control information (defined later in the section) to all backups.

Upon delivering a committing transaction, each database server executes a validation test to decide to commit or abort the transaction and sends the transaction's outcome to the client. The validation test depends on the delivery order of transactions. Since this order is the same for all servers and the validation test is deterministic, no two servers reach different outcomes (i.e., commit or abort) for the same transaction.

If a database server decides to commit the transaction, it executes the SQL statements associated with the transaction against the local database, making sure that if two transactions t_1 and t_2 have to be committed, and t_1 is delivered before t_2, t_1's SQL statements are executed before t_2's SQL statements.

As a response to the commit request, a client will eventually receive the transaction's outcome from the primary or from the backup servers or from both. If the outcome is commit, the client issues a response for job j. Otherwise the client has to re-execute job j. A server may also decide to abort a transaction during its execution if it finds out that

the transaction is involved in a (local) deadlock or it suspects that the client submitting the transaction has crashed.

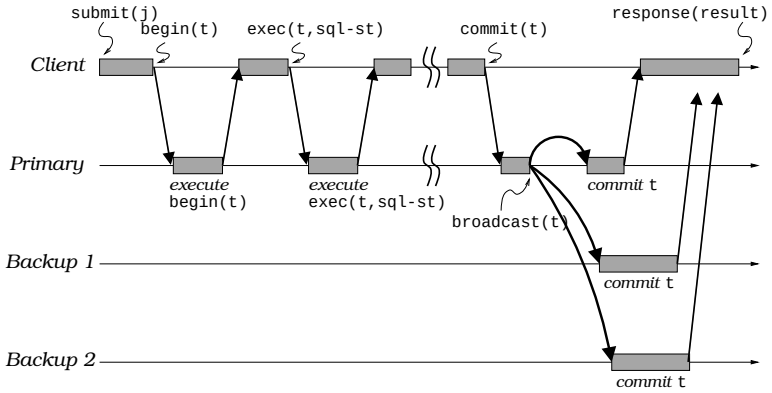

Figure 1: Pronto without crashes and suspicions

Failure/Suspicion Handling. After submitting a request, a client c may suspect the primary s to have crashed. This may happen because s has crashed or because c incorrectly suspects s. In either case, c sends an abort transaction message to s (just in case it was a false suspicion), chooses another database server s', and re-executes j (by sending the begin transaction request) using s'.

If the primary crashes or is suspected to have crashed, the execution evolves as a sequence of *epochs*;[3] in executions in which the primary does not crash nor is suspected to have crashed, however, there is only one epoch. During an epoch, there can only exist one primary, which is deterministically computed from the epoch number.

The epoch change mechanism works as follows. When a backup suspects the primary to have crashed, it broadcasts a message to all database servers to change the current epoch (which will result in another database server as the primary). A backup may suspect the current primary incorrectly. In such a case, the primary also delivers the change epoch message, and will abort all transactions in execution and inform the application servers corresponding to these transactions that a new epoch has started with a new primary.

[3]The notion of epoch used in Pronto differs from the one in [17]. Epochs are used in [17] to synchronize the installation of log records coming from transactions that executed at primary sites.

Clients have to re-start the execution of their jobs in the new primary, as described before.

Due to the unreliable nature of the failure detection mechanism used by database servers and the time it takes for messages to reach their destinations, it is possible that at a given time during the execution, database servers disagree on the current epoch, and so, multiple primaries may actually be able to process transactions simultaneously.

To prevent database inconsistencies (i.e., non-serializable executions) that may arise from transactions executing concurrently on different primaries, a transaction passes a validation test before committing. In order to do that, every transaction is broadcast together with the epoch in which it executed. The validation test ensures that a transaction is only committed by some database server if the epoch in which the database server delivers the transaction and the epoch in which the transaction was executed are the same.

Figure 2 depicts a scenario where two primaries try to commit transactions t and t'. When Primary 1 broadcasts transaction t, it has not delivered the new epoch message. Transaction t is delivered after the new epoch message, and so, it is aborted since t did not execute in the epoch in which it is delivered. Transaction t' is committed by every database server after it is delivered since it executed and is delivered in the same epoch. Although not shown in Figure 2, after validating a transaction, each database server sends the transaction outcome to the client.

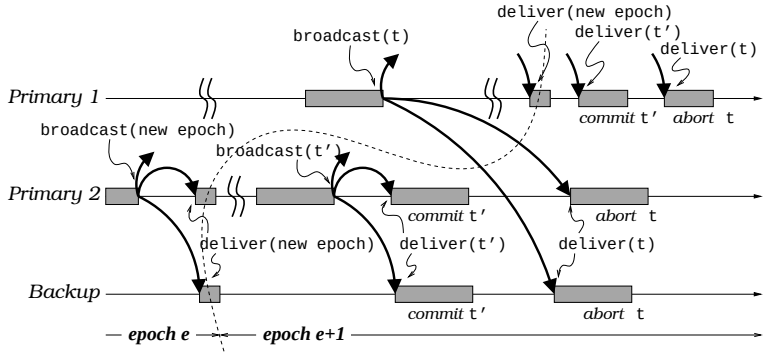

Figure 2: Two primaries scenario

Transactions pass through some well-defined states. A transaction starts in the executing state and remains in this state until a commit or abort is requested. If the client

requests to commit the transaction, the transaction passes to the committing state and is broadcast to all database servers by the primary. A transaction delivered by a database server is in the committing state, and it remains in the committing state until its fate is known by the database server (i.e., commit or abort). The executing and committing states are transitory states, whereas the committed and aborted states are final states.

3.2 The Detailed Algorithm

Algorithm 1 is the client side of the Pronto protocol. The algorithm is divided into two parts. In the first part, the client locates the primary server, and in the second part the client executes the transactional job. A transactional job is modeled as a function that receives the results from the previous request to generate the next request. The first request generated by a job j_a is $\texttt{begin}(t_a)$ (i.e., $j_a(\perp) = \texttt{begin}(t_a)$).

- **Locating the primary server (lines 2-14).** Initially, the client chooses one database server (lines 7-8), tries to start the transaction on this server (line 9), and waits for an answer or suspects the server to have crashed (line 10). If the client suspects the server to have crashed (line 11), the client chooses another server and, as before, tries to start the transaction on this server. Notice that client c suspects database server process s if $s \in \mathcal{D}_c$.

- **Executing a transactional job (lines 15-25).** The client sends the transaction requests, resulting from the execution of the transactional job, to the primary. After sending a request (line 17), the client waits until it receives an answer or it suspects the primary to have crashed (line 18). In the latter case, the client sends an abort request to the primary and starts again, possibly with a different primary. The message sent by the client is an optimization, which in case of a wrong suspicion, will not leave the transaction hanging in the server and possibly blocking other transactions. If the primary decides to abort the transaction, the client re-executes the job using the same database server. A suspicion leads the client to loop back to the first part of the algorithm, and re-execute the job on a new primary, if the previous has crashed.

In both parts of the algorithm, when a client suspects a primary p_c (lines 11 and 19), before trying to execute the transaction in another server, the client sends an abort transaction message to p_c (lines 12 and 20). This is done because the client may falsely suspect the primary, and in this case, before starting a new transaction, the client terminates the previous one.

Algorithm 1 Database client c

```
 1: To execute submit(j_a)...

 2:   p_c ← 0
 3:   findPrimary ← true
 4:   repeat
 5:     repeat
 6:       request ← j_a(⊥)
 7:       if findPrimary = true then
 8:         p_c ← (p_c mod n) + 1
 9:       send (t_a, request) to p_c
10:       wait until (receive (t_a, result) from p_c) or (p_c ∈ D_c)
11:       if not(received (t_a, result) from p_c) then
12:         send (t_a, abort(t_a)) to p_c
13:     until (received (t_a, result) from p_c) and (result ≠ "I'M NOT PRIMARY")
14:     findPrimary ← false

15:     repeat
16:       request ← j_a(result)
17:       send (t_a, request) to p_c
18:       wait until (receive (t_a, result) or (p_c ∈ D_c)
19:       if not(received (t_a, result) from p_c) then
20:         send (t_a, abort(t_a)) to p_c
21:         result ← ABORT
22:         findPrimary ← true
23:     until (result = COMMIT) or (result = ABORT)
24:   until (request = ABORT) or (request = COMMIT and result ≠ ABORT)
25:   response(result)
```

Algorithm 2 is the server side of the Pronto protocol. Except for lines 15-19, the algorithm is executed as a single task with several entry points (lines 5, 28, 44, and 46). For brevity, we do not present the server code handling transactions aborted by a database during their execution (e.g., due to a local deadlock).

- **Executing transactions (lines 5-26).** This is the primary's main procedure. If a client sends a `begin`(t_a) request to a backup, the backup refuses to process the

Algorithm 2 Database server s_i

```
1: Initialization...

2:    e_i ← 1
3:    p_i ← 1

4: To execute a transaction...

5: when receive (request) from c
6:    case request = begin(t_a):
7:       if s_i ≠ p_i then
8:          send (e_i, t_a, "I'M NOT PRIMARY") to c
9:       else
10:         state(t_a) ← EXECUTING
11:         begin(t_a)
12:         wait for response (t_a, result)
13:         send (t_a, result) to c
14:   case (request = exec(t_a, sql-st)) and (state(t_a) = EXECUTING):
15:      exec task
16:         exec(t_a, sql-st)
17:         wait for response(t_a, result)
18:         if result = ABORTED then state(t_a) ← ABORTED
19:         send (t_a, result) to c
20:   case (request = commit(t_a)) and (state(t_a) = EXECUTING):
21:      state(t_a) ← COMMITTING
22:      sqlSeq(t_a) ← all exec(t_a, sql-st) in order
23:      broadcast(s_i, e_i, c, t_a, sqlSeq(t_a))
24:   case (request = abort(t_a)) and (state(t_a) = EXECUTING):
25:      state(t_a) ← ABORTED
26:      abort(t_a)

27: To commit a transaction...

28: when deliver(s_j, e_j, c, t_a, sqlSeq(t_a))
29:   if e_j < e_i then
30:      state(t_a) ← ABORTED
31:      abort(t_a)
32:   else
33:      if s_i ≠ p_i then
34:         state(t_a) ← COMMITTING
35:         begin(t_a)
36:         for each exec(t_a, sql-st) ∈ sqlSeq(t_a) do
37:            exec(t_a, sql-st)
38:            wait for response(t_a, result)
39:      commit(t_a)
40:      wait for response(t_a, result)
41:      state(t_a) ← COMMITTED
42:   send (t_a, state(t_a)) to c
```

Algorithm 2 (cont.) Database server s_i

```
43: To change an epoch...

44: when p_i ∈ D_i
45:   broadcast(e_i, "NEW EPOCH")

46: when deliver(e_j, "NEW EPOCH") and (e_j = e_i)
47:   if p_i = s_i then
48:     for every t_a such that state(t_a) = EXECUTING do
49:       state(t_a) ← ABORTED
50:       abort(t_a)
51:       send (t_a, ABORTED) to c
52:   p_i ← (e_i mod n) + 1
53:   e_i ← e_i + 1
```

request (lines 7-8), but if the client sends the `begin`(t_a) request to the primary, the primary initializes the transaction's state (lines 10-12) and returns an acknowledgement that the database is ready to process `exec`($t_a, -$) requests. If the request is an `exec`(t_a,*sql-st*), the server executes it as an independent task (lines 15-19). This is done to prevent the server from executing requests sequentially against the database. If the primary receives a commit request for transaction t_a, it updates t_a's current state to committing (line 21), and broadcasts t_a's identifier, the epoch when t_a executed, the client identifier associated with t_a, and t_a's operations to all database servers (line 23). The `exec`($t_a, -$) statements are broadcast as a sequence. This allows the backups to execute t_a's requests in the same order as they were executed by the primary.

- **Committing transactions (lines 28-42).** Committing transactions are delivered by the *when* statement at line 28. After delivering some transaction t_a, a server first validates t_a (line 29). The validation consists in checking whether the epoch in which t_a executed is the current epoch. If it is not, t_a is aborted by the server (lines 30-31). If t_a executed in the current epoch, t_a passes the validation test and is locally committed (lines 33-41). At the primary, committing t_a consists of issuing a database commit request and waiting for the response (lines 39-40). At the backups, committing t_a consists of executing all t_a's `exec`($t_a, -$) operations (lines 34-38), issuing a database commit operation, and waiting for the response.

- **Changing epochs (lines 44-53).** The *when* statements at lines 44 and 46 handle epoch changes. When a server s suspects the current primary to have crashed, s broadcasts a 'new epoch' message (lines 44-45). Upon delivering the 'new epoch' message, a server determines the new primary from the epoch number (line 52) and updates the current epoch (line 53). If the primary has not crashed (i.e., in case of false suspicion), it also delivers the 'new epoch' message, and before passing to the next epoch, it aborts all local transactions in execution (lines 48-51). Aborting local transactions in execution before passing to the next epoch is an optimization as no such transactions will pass the validation test: these transactions will not be delivered in the epoch in which they executed.

3.3 Exactly-Once Transactional Jobs

In some systems, it is crucial to ensure that a transactional job commits only a single transaction in each database. Consider the case of a client that detects the crash of the current primary server. To ensure progress, the client may have to re-execute its transactional job against the new primary. However, if the former primary has managed to execute the client's job to completion (e.g., it failed after committing the transaction but before notifying the client), in the end two transactions will be committed by the new primary as the result of a single transactional job execution. An exactly-once transactional job prevents such a case from happening.

There are several mechanisms to ensure the exactly-once property [16]. In principle, clients should assign unique identifiers to transactional jobs and servers should keep track of previously executed jobs, making sure that two transactions for the same job will not both commit. In Pronto, this check can be executed after a transaction commit request is delivered by the database. If a transaction for the same job has already been committed, the server aborts the second transaction and notifies the client. The client can also be notified before submitting the transaction, as soon as the server realizes that the job has already been dealt with.

Clients can obtain unique identifiers by combining a local monotonically increasing sequencer (e.g., the local clock) with their own unique identifiers (e.g., their IP addresses).

Keeping track of previously executed transactional jobs can be done in many ways. They can be kept in memory, and asynchronously written to disk, if it is unlikely that all servers simultaneously fail. Alternatively, they can be stored in the database as part of the committing transaction.

3.4 Database Recovery

Databases interact with each other in Pronto using only the underlying Atomic Broadcast abstraction. The agreement and total order properties of Atomic Broadcast ensure a natural way to deal with database recovery: While agreement forces failing databases to deliver missed transactions upon recovery, total order prevents a failing database from delivering messages in the wrong order. This uniform treatment of failing and operational databases ensures that once a database recovers, the order in which it committed its transactions is consistent with the order other databases committed the same transactions.

Known Atomic Broadcast protocols implement uniform agreement and total order in the presence of crash and recovery in different ways [28, 41]. The protocol in [41], for example, allows a recovering process to retrieve the entire history of delivered messages. That is, the recovering process has access to all messages it delivered before it crashed and all messages that other processes delivered while it was down. In its simplest form, a recovering process in Pronto would have to replay the entire history of delivered messages. This would bring the epoch variable e_i up to date, and it would execute all transactions that the process missed while it was down. Notice that the exactly-once mechanisms discussed in Section 3.3 ensure that transactions are not re-executed during recovery.

Even though such an approach hides the complexities related to recovery, it may not be efficient if the recovering database has missed "too many" transactions: the cost of catching up with the operational databases by processing missing transactions may become higher than simply copying the database from an up-to-date site. A more general discussion about how to efficiently integrate group communication primitives and database recovery is beyond the scope of this paper. For further reference see, e.g., [25, 6, 22].

4 Evaluation of the Protocol

4.1 Analytical Evaluation

In a system with a single database server, when a client requests the commit of some transaction, the server tries to execute the commit operation against the database, and returns the answer to the client. In the Pronto protocol, before a server tries to execute the commit operation, it has to deliver and validate the transaction. Since the validation test is very simple (actually an integer comparison), the overhead introduced in the transaction response time by the Pronto protocol is expected to be mostly due to the broadcast primitive.

To discuss the cost of broadcasting transactions, we consider the Optimistic Atomic Broadcast algorithm [35] (OPT-broadcast) and the Paxos algorithm [29]. Both algorithms are non-blocking and tolerate an infinite number of false failure suspicions.

The OPT-broadcast makes the optimistic assumption that in some networks there is a good probability that messages arrive at their destinations in a total order. When this assumption holds, messages can be delivered "fast"; when it does not, the algorithm incurs in further computation to ensure that total order is preserved [35]. If δ is the transmission delay along communication links, then the *latency*, that is, the time between the primary broadcasts and delivers a transaction, is 2δ. When communication between servers is point-to-point, OPT-broadcast injects $(n+1)(n-1)$ messages in the network, where n is the number of servers. If a network-level broadcast primitive is available (e.g., IP-multicast), then $(n+1)$ messages are generated per broadcast.

The complete Paxos protocol has latency of 4δ. It injects $5(n-1)$ messages when communication is point-to-point, and $2(n+1)$ messages when communication uses network-level broadcast. If most messages are broadcast by the same sender, which is the expected behavior of Pronto, where most messages are update transactions broadcast by the primary, the protocol can be optimized leading to a latency of 2δ, and $3(n-1)$ and $n+1$ messages for point-to-point and low-level broadcast communication, respectively. Backups rely on the original protocol.

As a reference, we also consider the performance of 1-safe and 2-safe primary-backup replication [20]. Although [20] considers a single backup, we have specified the com-

plexity for $n-1$ backups. Using the 1-safe configuration, the primary can commit a transaction before exchanging messages with the backups, however, the backups may miss some transactions if the primary crashes. This leads to zero latency, and $n-1$ point-to-point messages or 1 network-level broadcast. To commit a transaction using the 2-safe configuration, the primary has to wait for a round-trip message with each backup. If the primary crashes, 2-safe guarantees that the backups have all transactions committed by the primary. However, in order to ensure consistency (i.e., at most one primary at a time), 2-safe techniques rely on accurate failure detection. This approach has a latency of 2δ, and injects $2(n-1)$ and n messages in the network for cases in which communication is by point-to-point and low-level broadcast, respectively.

Table 1 compares Pronto with OPT-broadcast and Paxos, 1-safe, and 2-safe. This comparison is only done for reference purposes since the 1-safe and 2-safe approaches make different assumptions about the underlying system and ensure different guarantees than Pronto with OPT-broadcast and Paxos. Pronto equipped with OPT-broadcast and optimized Paxos has the same latency as 2-safe. As for the number of messages, in point-to-point networks OPT-broadcast is $\mathcal{O}(n^2)$ while the other approaches are $\mathcal{O}(n)$. The message complexity of OPT-broadcast could be reduced to $\mathcal{O}(n)$ at the expense of an increase of one δ unit in the latency. If the network provides a low-level broadcast primitive, OPT-broadcast and optimized Paxos inject about the same number of messages as 2-safe. We notice however that false failure detection may lead to inconsistencies with 2-safe. With Pronto, false failure suspicions may prevent transactions from committing temporally, but consistency is always ensured.

Protocol / Approach	**Latency**	**Point-to-point messages**	**Broadcast messages**	**Remarks**
OPT-broadcast	$2\ \delta$	$(n+1)(n-1)$	$n+1$	optimistic order
Paxos	$4\ \delta$	$5\ (n-1)$	$2\ (n+1)$	general case
Paxos (optimized)	$2\ \delta$	$3\ (n-1)$	$n+1$	adapted to Pronto
1-safe	0	$n-1$	1	lost transactions
2-safe	$2\ \delta$	$2\ (n-1)$	n	accurate timeouts

Table 1: Cost of terminating a transaction

4.2 Pronto Prototype

We built a simple prototype to assess the overhead introduced by Pronto relative to a non-replicated configuration. In the prototype, every server has several execution threads and one communication thread. Each execution thread can execute one transaction at a time against the local database (i.e., the JDBC model). The communication thread implements atomic broadcast. At the backups, only one execution thread is active; the others simply wait for the server to become primary. Transactions are generated locally at the primary server.

Each execution thread has a JDBC connection to the local database, through which it sends SQL requests. After sending a request to the database, the thread waits for its response. If the request is a commit operation, before forwarding it to the database, the thread sends all SQL requests to the other servers, starting the broadcast execution for this transaction. The broadcast execution is then continued by the communication thread in the primary and in the backups.

Atomic broadcast is implemented based on the optimized Paxos protocol [29]. All messages are exchanged using TCP/IP. In the absence of failures and failure suspicions, a broadcast results in a message from the primary to all backups, an acknowledge message from each backup to the primary, and a final message from the primary to the backups. The primary can deliver the transaction after it receives an acknowledgment from a majority of servers (including itself). Backups deliver the transaction upon receipt of the second message from the primary. In case of failures and failure suspicions, more messages are exchanged to ensure that whatever delivery order is chosen by the primary is always respected by any future primary [29]. We assume that there is always a majority of servers up, and do not execute a synchronous logging as part of the broadcast [5].

After the execution thread broadcasts a transaction, it waits for a local event corresponding to its delivery. This event is raised by the communication thread once the transaction is delivered. The execution thread reacts to the delivery event by certifying the transaction. If the transaction passes the certification test, the execution thread sends a commit operation to the database; otherwise, it sends an abort operation.

Concurrent transactions never have their order reversed due to non-determinism of

thread execution. To see why, consider threads T_1 and T_2 executing two transactions, t_a and t_b, concurrently. If t_a and t_b conflict, there is some data item they both try to access. The first transaction that succeeds to hold a lock on the data, say t_a, proceeds but the second one, t_b, will be blocked by the database. Therefore, T_2 will not have a chance to broadcast t_b until t_b can access the requested data item, and t_b will only access the data item after t_a releases its locks. Transaction t_a will release its locks after it is delivered, and thus, it cannot be that t_b will be committed before t_a.

4.3 The Experiments' Setup

For the experiments, we used three database servers connected through a 10 MBit Ethernet network. The Primary executes in a 550 MHz Pentium III CPU with 256 MByte RAM; one of the backups (hereafter, Backup 1) executes in a 600 MHz Pentium III CPU with 128 MByte RAM; the second backup (hereafter, Backup 2) executes in a 200 MHz Pentium Pro CPU with 128 MByte RAM. The Primary and Backup 2 run Windows NT 4.0, and Backup 1 runs Windows 2000 Professional. All servers run a commercial database, installed without any tuning. Communication with the database is through JDBC 2.0.

The database has 6 similar tables, `account0`, `account1`, ..., `account5`, with 10000 records each. A record is composed of 6 fields: `acct_num` (10 bytes), `name` (10 bytes), `branch_id` (1 byte), `balance` (10 bytes), and `temp` (10 bytes). Each table is indexed by the `acct_num` field.

We have considered only update transactions in the experiments since these are the ones that generate interactions between servers, and can slow down the failover mechanism. JDBC has API's that allow applications to distinguish queries from update transactions. Thus, the primary can use these API's to process queries only locally. Each transaction has between 1 and 6 write operations. The number of operations in a transaction, and the tables and entries they update are randomly generated following a uniform distribution. A typical SQL operation looks like '`update account0 set balance = 1000.00 where acct_num = 1234`'.

4.4 The Performance of Pronto

In our experiments, we varied the multiprogramming level (MPL), that is, the number of execution threads in the primary and the think time (THT), that is, the time an execution thread in the primary waits after it finishes one transaction and before it starts another one. Once a threads starts a transaction, it executes the transaction as fast as it can. The think time controls the rate of transactions executed by a single thread.

To build the graphs presented next, we conducted a series of experiments, each one with about 40000 transactions. The executions were broken up into segments of about 20 seconds. At the end of each segment, a sample of values of interest was taken (e.g., throughput, response time) and at the end of the execution, we calculated their mean value. To eliminate initial transients, the values sampled in the first segment were discarded. All mean values are presented with a confidence interval of 95%.

In each experiment we measured two aspects of system performance:

- *Response time.* The time it takes to execute a single transaction end-to-end at the Primary. The start time is measured immediately before initiating the transaction; the end time is measured immediately after committing the transaction. The response time is then the difference between the end time and start time.

- *Throughput.* The transactions per second that a server process commits. As for response time, the throughput is measured by the Primary. As previously described, the execution is divided into segments. The throughput of the execution is calculated as the average of the throughput of each segment.

4.4.1 The Cost of Replication

The graphs in Figures 3–6 show the overhead of running Pronto as compared to a non-replicated, single machine system. We quantify the overhead in terms of both response time and throughput.

The graphs in Figures 3 and 5 show the relationship between throughput and multiprogramming level for various think times. For each think time, we show a throughput graph for a single database system and a replicated database system. We can then determine the overhead of Pronto by comparing the graph for a single database system to the

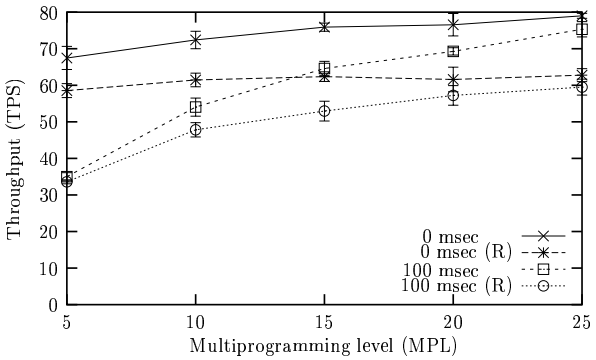

Figure 3: Ensemble throughput

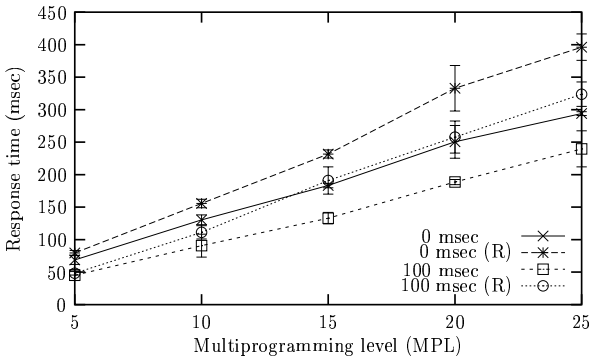

Figure 4: Ensemble response time

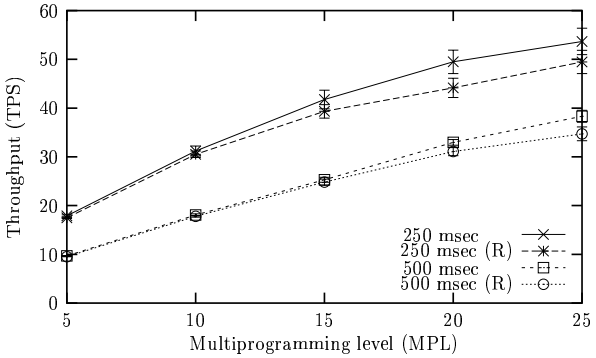

Figure 5: Ensemble throughput (cont.)

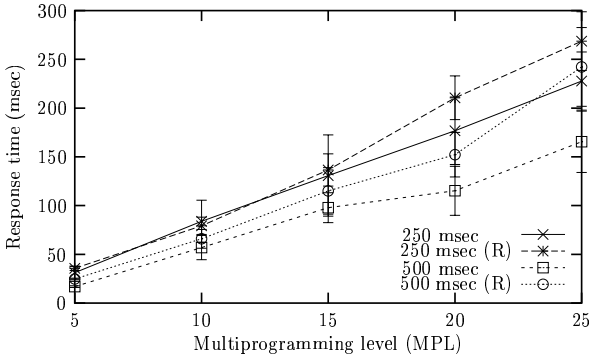

Figure 6: Ensemble response time (cont.)

graph for a replicated database system for a given think time. For example, for a think time of 0 (see Figure 3) running Pronto results in a throughput decrease of about 13% when the multi-programming level is 5 and 20% when the multi-programming level is 25. Moreover, a think time of 0 illustrates the worst-case scenario for Pronto. In this scenario, there is maximal contention for network resources. If instead we consider a think time of 500 msec (Figure 5), the overhead for any think time is less than 10%.

The graphs in Figures 4 and 6 quantify the response-time overhead of running Pronto. As for the throughput measurements, a response time graph shows the relationship between response time and multi-programming level for a given think time. Again, the worst-case overhead occurs with a think time of 0 and the maximum multi-programming level considered (i.e., 25). In this particular case, the response time overhead is about 26%. As can be seen from the response-time graphs, the higher the multi-programming level, the bigger the overhead of running Pronto. As the multi-programming level increases, so

does the contention for network resources.

4.4.2 Response Time Break-Down

In Figures 7 and 8 we show a break-down of the response time measurements—we show where the elapsed time was actually spent. For the break-down, we use three categories: (a) *Exec time*, the elapsed time for executing SQL statements through the JDBC interface, (b) *Abcast time*, the elapsed time (as seen by the primary server) of executing Atomic Broadcast, and (c) *Commit time*, the elapsed time to execute the transaction commit operation by the primary server.

Figures 7 and 8 show a response-time break-down for a think time of 0 and 500 msec, respectively. Both figures show the break down as "stacked" graphs, with Abcast time stacked on top of Exec time, and Commit time stacked on top of Abcast time. This means that a data point on the graph labeled Exec time is the actual measured value for Exec time. In contrast, a data point on the graph labeled Abcast time is the sum of the measured Abcast time and the measured Exec time. Furthermore, a data point on a graph labeled Commit time is the sum of the measured Commit time, the measured Abcast time, and the measured Exec time.Thus, the commit-time graph actually shows the end-to-end response time. The distance between the graphs in a given figure then denotes the actual break-down into categories.

As can be seen from the graphs, the time spent executing Atomic Broadcast increases as the multi-programming level increases. As indicated above, this effect explains why the cost of Pronto increases as the multi-programming level increases. Moreover, the system spends more time executing Atomic Broadcast with a think time of 0 as it does with a think time of 500 msec: We have more contention for network resources with a think time of 0 than we do with a think time of 500 msec.

4.4.3 Keeping Up with the Primary

Figures 9 and 10 show the relationship between the throughput in the primary, under various multi-programming levels and think times, and the throughput in the backups, with multi-programming level 1 and no think time. A ratio smaller than or equal to 1

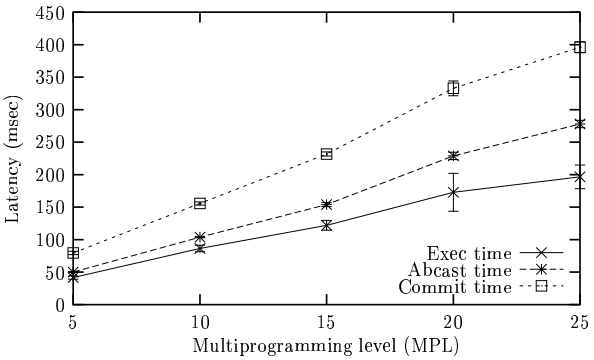

Figure 7: Resp.time break-down (THT=0)

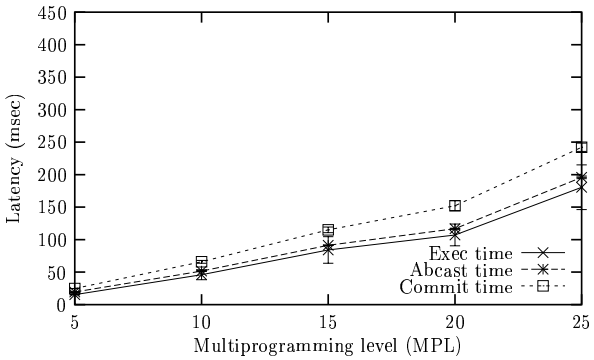

Figure 8: Resp.time break-down (THT=500)

means that the backup can process transactions faster than or as fast as the primary; a ratio greater than 1 means that the backup is slower than the primary. If the backup cannot process transactions as fast as the primary, transactions will have to be queued. If the workload is constant, the ratio gives a measure of the growth rate of the backup queue.

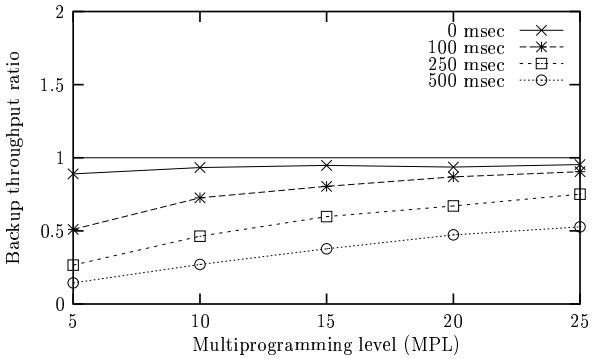

Figure 9: Throughput ratio (Backup 1)

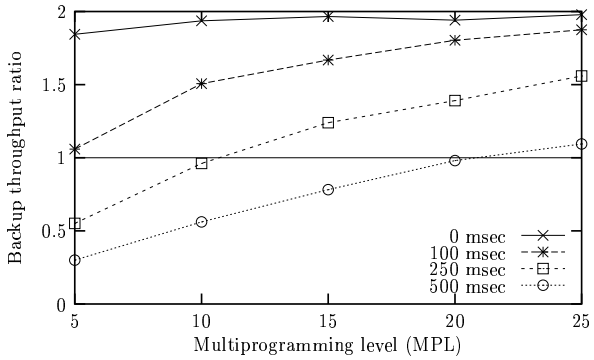

Figure 10: Throughput ratio (Backup 2)

From Figure 9, Backup 1 never lags behind the primary (i.e., for every multi-programming level and think time, the throughput ratio in Backup 1 is smaller than 1). The same does not hold for Backup 2. Figure 10 shows that Backup 2 cannot process transactions as fast as the primary when the think time is 0 or 100 msec. Nevertheless, Backup 2 can keep up with the primary when the think time is 250 msec and the multi-programming level below 10, and the think time is 500 msec and the multi-programming level below 20.

5 Conclusion

This paper presents Pronto, a protocol that allows clients to access an ensemble of databases as if it were a single database. Clients access the ensemble through a standard interface, such as JDBC. The benefit of using an ensemble instead of a single database is that the ensemble can provide un-interrupted service in the presence of database failures. This capability provides a highly-available transaction-processing system, and allows enterprise applications to be continuously available.

Pronto relies on practical assumptions: clients access databases through standard interfaces, databases from different vendors can be part of the ensemble (the only requirement is to support the standard interfaces), and the correctness of the system does not need perfect failure detection. Performance evaluation conducted with a prototype in an environment composed of off-the-shelf databases has shown that Pronto can synchronize the database ensemble with a reasonable performance overhead.

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Appendix

For the following proofs, $C(\mathcal{E}_i^e)$ is the committed projection of the execution $\mathcal{E}_i^e$, created by the Pronto protocol during epoch e at database server process s_i. $C(\mathcal{E}_i^e)$ is a partial order, that is, $C(\mathcal{E}_i^e) = (\Sigma_i^e, <_i^e)$, where Σ_i^e is the set of committed transactions in $\mathcal{E}_i^e$, and $<_i^e$ is a set defining a transitive binary relation between transactions in Σ_i^e. We define $C(\mathcal{E}^e) = C(\mathcal{E}_i^e) \cup C(\mathcal{E}_j^e)$ such that $\Sigma^e = \Sigma_i^e \cup \Sigma_j^e$ and $<^e = <_i^e \cup <_j^e$.

Lemma 1 *Let $s_{p(e)}$ be the primary database server at epoch e. For every backup server $s_{b(e)}$ that does not crash in epoch e, and all $e \geq 1$, $C(\mathcal{E}_{p(e)}^e) = C(\mathcal{E}_{b(e)}^e)$.*

PROOF (SKETCH): We have to show that database servers $s_{p(e)}$ and $s_{b(e)}$ commit the same transactions (i.e., $\Sigma_{p(e)}^e = \Sigma_{b(e)}^e$) in the same order (i.e., $<_{p(e)}^e = <_{b(e)}^e$). Assume that $s_{p(e)}$ commits transaction t during epoch e. Therefore, t passed the validation test, and so, $s_{p(e)}$ has executed t during epoch e, and has not delivered any message of the type (e, "NEW EPOCH") before delivering message $(s_{p(e)}, e, -, t, \texttt{sqlSeq}(t))$. From the agreement and total order properties of the broadcast primitive, server $s_{b(e)}$ also delivers message $(s_{p(e)}, e, -, t, \texttt{sqlSeq}(t))$ before delivering any message of the type (e, "NEW EPOCH"). Thus, t passes the validation test at $s_{b(e)}$ and is committed by $s_{b(e)}$.

We now show that $<_{p(e)}^e = <_{b(e)}^e$, that is, if a transaction t_a precedes another transaction t_b in $C(\mathcal{E}_{p(e)}^e)$, then t_a also precedes t_b in $C(\mathcal{E}_{b(e)}^e)$. Since server $s_{p(e)}$ executes transactions using a 2PL scheduler, if t_a precedes t_b, then t_a commits before t_b. From the algorihm, it follows that t_a is delivered before t_b. By total order of the broadcast primitive and the fact that backups commit transactions in the same order as they are delivered, server $s_{b(e)}$ delivers and commits t_a before t_b. Thus, t_a precedes t_b in database server $s_{b(e)}$. □

Lemma 2 *For any execution $\mathcal{E}$ of the Pronto protocol, there exists a serial execution $\mathcal{E}_s$ involving the committed transactions in $\mathcal{E}$, such that $C(\mathcal{E})$ is equivalent to $C(\mathcal{E}_s)$.*

PROOF (SKETCH): From property DB-1, for any execution $\mathcal{E}_{p(e)}^e$, at epoch e, there exists a serial execution $\mathcal{E}_s^e$, involving the committed transactions in $\mathcal{E}_{p(e)}^e$, such that $C(\mathcal{E}_{p(e)}^e)$ is equivalent to $C(\mathcal{E}_s^e)$. By Lemma 1, for every backup $s_{b(e)}$ that does not crash in epoch e, and all $e > 1$, $C(\mathcal{E}_{p(e)}^e) = C(\mathcal{E}_{b(e)}^e)$. Thus, from the definition of committed projection,

$C(\mathcal{E}^e_{p(e)}) \cup C(\mathcal{E}^e_{b_1(e)}) \cup ... \cup C(\mathcal{E}^e_{b_{m(e)-1}(e)}) = C(\mathcal{E}^e_{p(e)})$, where $m(e)$ is the number of database servers that do not crash in epoch e. Thus, $C(\mathcal{E}^e_{p(e)}) \cup C(\mathcal{E}^e_{b_1(e)}) \cup ... \cup C(\mathcal{E}^e_{b_{m(e)-1}(e)})$ is equivalent to $C(\mathcal{E}^e_s)$.

We claim that $\cup_{e=1} C(\mathcal{E}^e_s)$ is equivalent to $C(\mathcal{E}_s)$. The proof for the claim follows from the fact that for all $e \geq 1$, the Pronto protocol ensures that executions $\mathcal{E}^e_s$ and $\mathcal{E}^{e+1}_s$ are executed sequentially. That is, every transaction that executes in epoch $e+1$ starts after all transactions that commit in epoch e have been committed. We conclude that for any execution $\mathcal{E}$, there exists an execution $\mathcal{E}_s$, such that $C(\mathcal{E})$ is equivalent to $C(\mathcal{E}_s)$. □

Lemma 3 *If a client c executes* `submit`(j) *and does not crash, then c eventually executes* `response`$(result)$.

PROOF (SKETCH): We show that client c eventually contacts a primary that executes and commits a transaction t_a generated by j_a. The argument is that, firstly, no client blocks forever in the *wait* statements at lines 9 and 16. In both cases, if the primary crashes, the client suspects it, and tries to execute the job in another server. If the primary does not crash, it will send a response to the client: in the *wait* statement at line 9, the client has requested a `begin`$(-)$ operation, and a database is always able to execute it; in the *wait* statement at line 16, if the request cannot be processed by the primary (e.g., the transaction is deadlocked), the primary aborts the transaction and replies to the client.

Thus, a client could not execute job j if (a) it cannot find the primary, or (b) it finds the primary and starts executing the job in the primary but before terminating the job, the epoch changes and another server becomes primary (i.e., the transaction generated by the job is aborted due to an epoch change), or (c) the primary does not change but keeps aborting the transactions generated by j_a. Cases (a) and (b) never happen because there is a time when some server s_p that does not crash is not suspected by any other process to have crashed. s_p eventually becomes primary and remains primary forever. So, the client will eventually contact s_p, start a transaction on s_p, and never suspect s_p. Finally, alternative (c) contradicts database property DB-2: since s_p does not crash, c does not suspect it and keeps sending transactions generated by executions of j_a. So, eventually, one transaction terminates and j_a is successfully executed. We conclude that c eventually contacts a primary that executes and commits a transaction generated by j_a. □