Concurrency and Communication in Transaction Logic

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Abstract
In previous work, we developed Transaction Logic (or TR), which deals with state changes in deductive databases. TR provides a logical framework in which elementary database updates and queries can be combined into complex database transactions. TR accounts not only for the updates themselves, but also for important related problems, such as the order of update operations, non-determinism, and transaction failure and rollback. In the present paper, we propose Concurrent Transaction Logic (or CTR), which extends Transaction Logic with connectives for modeling the concurrent execution of complex processes. Concurrent processes in CTR execute in an interleaved fashion and can communicate and synchronize themselves. Like classical logic, CTR has a “Horn” fragment that has both a procedural and a declarative semantics, in which users can program and execute database transactions. CTR is thus a deductive database language that integrates concurrency, communication, and updates. All this is accomplished in a completely logical framework, including a natural model theory and a proof theory. Moreover, this framework is flexible enough to accommodate many different semantics for updates and deductive databases. For instance, not only can updates insert and delete tuples, they can also insert and delete null values, rules, or arbitrary logical formulas. Likewise, not only can databases have a classical semantics, they can also have the well-founded semantics, the stable-model semantics, etc. Finally, the proof theory for CTR has an efficient SLD-style proof procedure. As in the sequential version of the logic, this proof procedure not only finds proofs, it also executes concurrent transactions, finds their execution schedules, and updates the database. A main result is that the proof theory is sound and complete for the model theory.

1 Introduction

Updates are a crucial component of any database programming language. Even the simplest database operations, such as withdrawal from a bank account, require updates. Unfortunately, updates are not accounted for by the classical Horn semantics of deductive databases. To fill this theoretical gap, we developed Transaction Logic (or TR), an extension of first-order classical logic that provides a clean, logical account for state changes in databases and logic programs [6, 5, 7]. Like classical logic, TR has a “Horn” fragment that has both a procedural and a declarative semantics, in which users can program and execute database transactions. TR accounts not only for the updates themselves, but also for important related problems, such as the order of update operations, non-determinism, and transaction failure and rollback. All this is accomplished in a completely logical framework, including a natural model theory and a sound-and-complete proof theory.

One of the difficulties posed by updates in logic programs is that the order of update operations is often crucial. For example, erasing a database relation and inserting tuples into the relation are conflicting operations: the final outcome depends on which operation is executed first. The classical semantics of Horn logic does not address this issue. To deal with it, Transaction Logic extends classical logic with an operator—called serial conjunction—that allows a user to specify a linear order on a set of transactions. Using this operator in combination with logical rules, a user builds complex transactions out of simpler ones. This approach provides more flexibility and power than most other declarative database transaction languages. For instance, many such languages do not support subtransactions, transaction failure, or transaction rollback. Moreover, whereas most database transaction languages express all the database transactions computable in PSPACE, TR expresses all the transactions computable in EXPTIME (in the function-free case) [8].

In this paper, we extend Transaction Logic by allowing updates to be combined concurrently, as well as serially. We call the resulting logical system Concurrent Transaction Logic (or CTR). Like Transaction Logic, CTR is a language for programming database transactions and applications.\(^1\) Concurrency increases the flexibility, performance, and power of the

\(^1\) Consequently, this paper is about database application programming, not concurrency control.
language. Flexibility is increased since users are no longer forced to specify a total linear order on transactions. This opens the logic to a new range of advanced applications, including workflow management and multi-agent planning. Performance is increased since in a multi-user environment, a database management system (DBMS) can execute any concurrent process whose data items are available. It does not have to delay process execution because of an artificially-imposed linear order. Finally, power is increased since the logic can now express any computable database transaction [8], i.e., concurrency increases expressibility from EXP-TIME to RE (in the function-free case).

Although there has been considerable research on concurrency in databases, logic programming, and elsewhere, CTR is the only deductive database language that integrates concurrency, communication, and database updates in a completely logical framework. Such integration opens up new possibilities for the programmer. For instance, concurrent processes can communicate via the database; that is, one process can read what another process has written. This form of communication leads to a programming style that is very different from that of existing concurrent logic programming (CLP) languages, as illustrated in this paper. In CLP languages [24], concurrent processes communicate via shared variables and unification. This kind of communication is orthogonal to communication via the database. Both are possible in CTR. However, this possibility is not the focus of this paper. Instead, we focus on concurrent processes that interact and communicate via the database. Indeed, one of the novelties of CTR is that it provides a logical foundation for exactly this kind of interaction.

Programming with states is very common, and the practice of logic programming shows that it is also unavoidable. Unfortunately, classical logic is stateless. One way to get around this problem is to represent states as terms, as in the situation calculus [15, 23]. However, this approach has not taken root in logic programming for many reasons, including the complexity of dealing with the frame problem [7]. In Prolog, efficient techniques have been developed where states are represented as lists or terms, which do not require frame axioms. However, these techniques rely heavily on Prolog's control strategy, cuts, or on other non-logical features. Moreover, it is not clear that this approach is practical for very large states, such as databases. Only “tiny” databases fit in main memory, and databases several gigabytes in size are commonplace. Can Prolog efficiently manage a 10 GByte list? What if several processes need to modify the list concurrently?

Another problem is that updates in Prolog are not integrated into a complete logical system. Thus, it is not clear how assert and retract should interact with other logical operators. For instance, what do the following formulas mean: assert(X) ∨ assert(Y), ∀X∀Y assert(p(X, Y)), assert(X) ← retract(Y), or ¬assert(X). Also, how does one logically account for the fact that the order of updates is important? Finally, what does it mean to update a database that contains arbitrary logical formulas? None of these questions is addressed by Prolog's classical semantics or its update operators. Likewise, these problems are not addressed by existing concurrent logic programming languages [24]. In fact, the problems of updates are even more complex in a concurrent environment.

Concurrent Transaction Logic provides a general solution to the aforementioned limitations, both of Prolog and of concurrent logic programming languages. Intuitively, a CTR program consists of a number of concurrent processes, where each process produces a sequence of elementary database operations. By interleaving these sequences, we obtain a new sequence of operations, which can then be executed. The set of possible interleavings is determined by interactions between the processes. For instance, if one process writes data that another process must read, then the write operation must come before the read operation in the interleaved sequence. These interactions are specified by CTR programs. Given such a program, the model theory describes the set of all possible interleavings, and the proof theory generates them.

From the programmer's point of view, CTR supplies a syntax and a semantics by which elementary database operations can be combined serially and concurrently into complex programs. Like sequential Transaction Logic, the emphasis in CTR is not on specifying elementary operations, but on combining them logically into programs. This emphasis reflects programming practice. In database and logic programming (as in C and Pascal), application programmers spend little if any time specifying elementary operations, but a lot of time combining them into complex transactions and programs.

Nevertheless, the set of elementary operations is an important feature of a language, and can determine its domain of application. Moreover, practice shows that elementary operations can vary widely. For example, in C and Pascal, changing the value of a variable is an elementary operation. In Prolog, asserting or retracting a clause is elementary. In database applications, SQL statements are the basic building blocks. In scientific and engineering programs, basic
operations include Fourier transforms, matrix inversion, least-squares fitting, etc. In workflow management systems, elementary operations can include any number of application programs and legacy systems [3]. In all cases, the elementary operations are building blocks from which larger programs and software systems are built.

Although elementary operations vary dramatically, the logic for combining them does not and the same control features arise over-and-over again. These include sequential and concurrent composition, iterative loops, conditionals, subroutines and recursion. CTR provides a logical framework in which these control features can be expressed. This framework is orthogonal to the elementary operations. CTR can therefore be used with any set of elementary database operations, including destructive updates. To achieve this flexibility, CTR treats a database as a collection of abstract datatypes, each with its own special-purpose access methods. These methods are provided to CTR as elementary operations, and they are combined by CTR programs into complex transactions. This approach separates the specification of elementary operations from the logic of combining them. As we shall see, this separation has two main benefits: (i) it allows us to develop a logic language for programming state-changing programs without committing to a particular theory of elementary updates; and (ii) it allows CTR to accommodate a wide variety of database semantics, from classical to non-monotonic to various other non-standard logics. In this way, CTR provides the logical foundations for extending the logic-programming paradigm to a host of new applications in which a given set of operations must be combined into larger programs or software systems.

2 Syntax

2.1 Transaction Formulas

The alphabet of a CTR language L includes three countable sets of symbols: a set F of function symbols, a set V of variables, and a set P of predicate symbols. Each function and predicate symbol has an associated arity, indicating how many arguments the symbol takes. Constants are viewed as 0-ary function symbols, and propositions are viewed as 0-ary predicate symbols. The language L also includes the logical connectives ∧, ⊕, |, →, the modal operator ⊙, and the quantifier ∨. Function terms are defined as usual in first-order logic.

As the alphabet suggests, transaction formulas extend first-order formulas with two new connectives, ⊕ and |, which we call serial disjunction and concurrent disjunction, respectively, and one modal operator ⊙ for specifying atomic actions. The simplest transaction formulas are atomic formulas, which are defined as in classical logic via predicates and terms. In addition, if φ and ψ are transaction formulas, then so are φ ∧ ψ, φ ⊕ ψ, φ | ψ, → φ, ⊙ φ, and (∀X)φ, where X is a variable. Intuitively, the formula φ ⊕ ψ means that the subtransactions φ and ψ execute serially, i.e., first φ executes to completion, and then ψ executes. The formula φ | ψ means that the subtransactions φ and ψ execute concurrently. The formula ⊙ φ means that φ must execute "atomically," meaning that its execution should not be interleaved with other transactions. Note that classical first-order formulas are transaction formulas that do not use the connectives ⊕, |, or the modal operator ⊙. As in classical logic, we introduce convenient abbreviations for complex formulas. For instance, φ ↔ ψ is an abbreviation for φ ∨ ¬ψ. Likewise, ψ ∨ ¬φ is an abbreviation for ¬(¬φ ∧ ¬ψ), and φ ∨ ψ is an abbreviation for ¬(¬φ ∧ ¬ψ). Other useful abbreviations are developed in [7]. Here are three examples of transaction formulas:

\[(a \circ b) | (c \circ d), \quad a(X) \leftarrow [b(X) \mid c(X, Y)], \quad \forall X[a(X) \lor \neg b(X) \circ \neg c(X, Y)]\]

2.2 Database States, Elementary Operations, and Oracles

Logical theories always come with a parameter: a language for constructing well-formed formulas. This language is not fixed, since almost any set of constants, variables and predicate symbols can be "plugged into" it. In addition, CTR theories have another parameter: a pair of oracles that encapsulate elementary database operations. Like the language of the logic, the oracles are not fixed, since almost any pair of oracles can be "plugged into" a CTR theory. The oracles come with a set of database states, upon which they operate. In practice, we expect that each database state will be a set of data items, as in the theory of transaction management [2]. Intuitively, a data item can be any kind of persistent object, such as a tuple, a disk page, an email queue, or a logical formula. Formally, however, a database state has no structure, and our only access to it is through the two oracles.

Both oracles are mappings. The data oracle, O, is a mapping from states to sets of first-order formulas. Intuitively, if D is a state, then O(D) is the set of formulas that are true of the state. Likewise, the transition oracle, O, is a mapping from pairs of states to sets of ground atomic formulas. Intuitively, if b ∈ O(D1, D2) then b is an elementary update that changes state D1 into state D2. Primitive data access is thus specified outside CTR, by using the oracles. The oracles also provide a semantics for the data items: the data oracle provides a static semantics; and the transition oracle provides a dynamic semantics, that is, a semantics of

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2 Ground atomic formulas are required for simplicity.
change. By using oracles in this way, CTR can accommodate different data access primitives and different database semantics.

Here are some examples of data and transition oracles. Some of these can be combined to yield more powerful oracles. Typically, such combinations are possible when oracles operate on disjoint domains of data items.

Relational Oracles: A state is a set of ground atomic formulas, \( D \). The data oracle simply returns all these formulas. Thus, \( \mathcal{O}^d(D) = D \). Moreover, for each predicate symbol \( p \) in \( D \), the transition oracle defines two new predicates, \( p . \text{ins} \) and \( p . \text{del} \), representing the insertion and deletion of single atoms, respectively. Formally, \( p . \text{ins}(\tau) \in \mathcal{O}^d(D_1, D_2) \) iff \( D_2 = D_1 \cup \{ p(\tau) \} \). Likewise, \( p . \text{del}(\tau) \in \mathcal{O}^d(D_1, D_2) \) iff \( D_2 = D_1 - \{ p(\tau) \} \). SQL-style bulk updates can also be defined by the transition oracle [7], as can primitives for creating new constant symbols.

Horn Oracles: A state \( D \) is a set of Horn rules and \( \mathcal{O}^d(D) \) is the minimal Herbrand model of \( D \). One may also want to augment \( \mathcal{O}^d(D) \) with the rules from \( D \). The transition oracle can be defined to insert and delete Horn rules from \( D \).

Communication Oracles: A state is a set of message queues, each representing a communication channel. Each queue has a name, \( q \), and a list of messages. The data oracle defines a binary predicate, \( \text{peek} \), which corresponds to reading a message without consuming it. Formally, \( \text{peek}(q, \text{msg}) \in \mathcal{O}^d(D) \) iff the front of queue \( q \) in \( D \) has the message \( \text{msg} \). The transition oracle defines two binary predicates, \( \text{send} \) and \( \text{receive} \), which correspond to sending and receiving messages along a communication channel. Formally, \( \text{send}(q, \text{msg}) \in \mathcal{O}^d(D_1, D_2) \) iff \( D_2 \) is obtained from \( D_1 \) by adding \( \text{msg} \) to the end of queue \( q \). Likewise, \( \text{receive}(q, \text{msg}) \in \mathcal{O}^d(D_1, D_2) \) if \( q \) in \( D_1 \) has the message \( \text{msg} \), and \( D_2 \) is obtained from \( D_1 \) by removing \( \text{msg} \) from the front of \( q \). Intuitively, \( \text{receive} \) reads a message on channel \( q \) and consumes it. Other communication primitives, such as creating and destroying channels, can also be defined by the oracles.3

Unlike transaction formulas, we do not expect the oracles to be coded by casual users. Although the oracles allow for many different semantics, we envision that any logic programming system based on CTR will provide a carefully selected repertoire of built-in database semantics and a tightly controlled mechanism for adding new ones. This latter mechanism would not be available to ordinary programmers. For this reason, we assume in this paper that the data and transition oracles are fixed. For a more complete discussion of data and transition oracles, see [7].

2.3 Examples

This section gives some simple examples of Concurrent Transaction Logic programs, or transaction bases. A transaction base is a finite set of transaction formulas. In this paper, all examples of transaction bases use so-called concurrent Horn rules, which are defined formally in Section 4. The body of these rules consists of atomic formulas connected by serial or concurrent conjunction. Atomic modalities are also allowed. Each atomic formula stands for a query, an update or, more generally, a transaction. For example, the formula \( a \leftarrow (b_1 \otimes b_2) \cup (c_1 \otimes c_2) \) is a concurrent Horn rule. Intuitively, it says, "To execute transaction \( a \), execute concurrently the two transactions \( b_1 \otimes b_2 \) and \( c_1 \otimes c_2 \). To execute \( b_1 \otimes b_2 \), first do \( b_1 \) then \( b_2 \), and similarly for \( c_1 \otimes c_2 \)." The rule-head, therefore, acts as the name of a transaction, while the rule-body acts as the transaction definition.

All examples in this paper are based on a combination of the relational and communication oracles defined in Section 2.2. A state is a collection of ground atomic formulas and communication channels (queues). A relation \( p \) is accessed by using the predicates \( p . \text{ins} \) and \( p . \text{del} \). Communication takes place using the predicates \( \text{send} \), \( \text{receive} \), and \( \text{peek} \). Formally, these predicates are different from other predicates, and their fancy names is a mere convention. Their special status, however, comes from the choice of the data and transition oracles.

The first example, below, focuses on serial conjunction and shows how updates can be combined with queries to define complex transactions. It also illustrates the use of transaction subroutines (or nested transactions), and shows how Transaction Logic improves upon Prolog's update operators.

Example 2.1 (Financial Transactions) Suppose the balance of a bank account is given by the relation \( \text{balance} (\text{Accnt}, \text{Amnt}) \). We define four transactions: \( \text{changeBalance} (\text{Accnt}, \text{Bal1}, \text{Bal2}) \), to change the balance of an account; \( \text{withdraw} (\text{Amnt}, \text{Accnt}) \), to withdraw from an account; \( \text{deposit} (\text{Amnt}, \text{Accnt}) \), to deposit into an account; and \( \text{transfer} (\text{Amnt}, \text{Accnt1}, \text{Accnt2}) \), to transfer an amount from one account to another. These transactions are defined by the following four rules, which form a transaction base:

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3It is important to keep in mind here that concurrency and communication are not built into the oracles in CTR. Communication oracles are just a matter of convenience. We shall see that all communication primitives can be expressed using CTR's logical connectives.
\[
\text{transfer}(\text{Amt}, \text{Acct1}, \text{Acct2}) \leftarrow \circ [\text{withdraw}(\text{Amt}, \text{Acct1}) \circ \text{deposit}(\text{Amt}, \text{Acct2})]
\]
\[
\text{withdraw}(\text{Amt, Acct}) \leftarrow \text{balance}(\text{Acct, Bal}) \circ \text{Bal} \geq \text{Amt}
\]
\[
\text{deposit}(\text{Amt, Acct}) \leftarrow \text{balance}(\text{Acct, Bal}) \circ \text{change_balance}(\text{Acct, Bal, Bal - Amt})
\]
\[
\text{change_balance}(\text{Acct, Bal1, Bal2}) \leftarrow \text{balance.del}(\text{Acct, Bal1}) \circ \text{balance.ins}(\text{Acct, Bal2})
\]

In each rule, the premises are evaluated from left to right—an evaluation order imposed by the serial conjunction. For instance, the first rule says: to transfer an amount, \text{Amt}, from \text{Acct1} to \text{Acct2}, first withdraw \text{Amt} from \text{Acct1} and, if the withdrawal succeeds, deposit \text{Amt} in \text{Acct2}. Likewise, the second rule says, to withdraw \text{Amt} from an account \text{Acct}, first retrieve the balance of the account; then check that the account will not be overdrawn by the transaction; if all is well, change the balance from \text{Bal} to \text{Bal - Amt}. Notice that the atom \text{balance(Acct, Bal)} is a query that retrieves the balance of the specified account, and \text{Bal} \geq \text{Amt} is a test. All other atoms in this example are updates. The last rule changes the balance of an account by deleting the old balance and then inserting the new one. Unlike the other rules, the last rule is defined via built-in, elementary updates, \text{balance.del} and \text{balance.ins}. Finally, observe that the entire transaction is atomic, as specified in the body of the first rule. Thus, if two transfers are carried out concurrently, then they will not interfere with each other. □

Observe that the rules in Example 2.1 can be cast into the Prolog syntax by replacing "\circ" with "," and replacing the elementary transitions, \text{balance.ins} and \text{balance.del}, with \text{assert} and \text{retract}, respectively. However, the resulting, apparently innocuous, Prolog program will not execute correctly! The problem is that Prolog does not undo updates during backtracking. As an example, consider a transaction involving two transfers, defined as follows:

\[
?- \text{transfer}(\text{Fee, Client, Broker}) \circ \text{transfer}(\text{Cost, Client, Seller})
\]

That is, a fee is transferred from a client to a broker, and then a cost is transferred from the client to a seller. Because this is intended to be a transaction, it must behave \text{atomically}; that is, it must execute entirely or not at all. Thus, if the second transfer fails, then the first one must be rolled back. In this respect, \text{CTR} behaves correctly. Prolog, however, does not, as it commits updates immediately and does not undo partially executed transactions. Thus, if the second transfer above were to fail (say, because the client's account would be overdrawn by the transaction), then Prolog would not undo the first one, leaving the database in an inconsistent state.

The non-logical behavior of Prolog updates is notorious for making Prolog programs cumbersome and heavily dependent on Prolog's backtracking strategy. Some Prologs do have the means to implement backtracking updates through the use of non-logical operations, such as \text{assert}, \text{retract}, and cut (!). However, the logic behind the resulting update operations has not been developed. Transaction Logic can be considered to provide the missing semantics and proof theory, although there are many fine differences between simplistic implementations of backtracking updates and our logic.

The above example illustrates some salient features of sequential Transaction Logic, but it consists of a single process that executes alone. Here is a simple example of two processes executing concurrently:

\[
?- \text{transfer}(\text{Fee, Client, Broker}) \mid \text{transfer}(\text{Cost, Client, Seller})
\]

Once again, because this is a transaction, it must behave \text{atomically}. Thus, if one transfer process fails, then the other one must be rolled back. The semantics of Concurrent Transaction Logic specifies exactly this. This illustrates the simplest way the combination of concurrency and updates that \text{CTR} supports. The next examples illustrate how \text{CTR} also supports communication. The first example shows how processes in Concurrent Transaction Logic can synchronize themselves by exchanging messages along communication channels.

\textbf{Example 2.2 (Synchronization)} Consider the following transaction base, which defines two processes, \text{processA} and \text{processB}:

\[
\text{processA} \leftarrow \text{taskA}_1 \circ \text{send}(\text{ch}_1, \text{start} B) \circ \text{taskA}_2 \circ \text{receive}(\text{ch}_2, \text{start A}) \circ \text{taskA}_3
\]
\[
\text{processB} \leftarrow \text{taskB}_1 \circ \text{receive}(\text{ch}_1, \text{start B}) \circ \text{taskB}_2 \circ \text{send}(\text{ch}_2, \text{start A}) \circ \text{taskB}_3
\]

Processes \text{processA} and \text{processB} invoke three tasks each. The transaction invocation

\[
?- \text{processA} \mid \text{processB}
\]

causes \text{processA} and \text{processB} to execute concurrently while synchronizing the execution of their tasks by passing messages along channels \text{ch}_1 and \text{ch}_2. In particular, \text{taskB}_2 cannot start executing until \text{taskA}_1 is finished, and \text{taskA}_3 cannot start executing until \text{taskB}_1 is finished.

While executing \text{taskA}_1 and \text{taskB}_1, the two processes run concurrently, without interacting with each other. However, when \text{processB} completes \text{taskB}_1, it cannot start \text{taskB}_2 until it receives a message from \text{processA}. To understand why, recall the definition of the communication oracle. The transition \text{receive}(\text{ch}_1, \text{start B}) cannot execute (which means it cannot be true on any execution path emanating from the current state—see Section 3) unless
the message \textit{start}B is sitting at the front of the queue \textit{ch1}. However, this message will not be there unless \textit{process}A makes the transition \textit{send(ch1, start}B), which will only happen after \textit{process}B executes \textit{task}A1. In this way, \textit{process}B is synchronized with \textit{process}A.

Similarly, on completing \textit{task}A2, \textit{process}A cannot start \textit{task}A3 until it receives a message from \textit{process}B, which will only happen after \textit{process}B executes \textit{task}B2. Note that CTR processes do not need a hand-shake in order to communicate (but hand-shake can be achieved by sending more messages). □

Example 2.3 (Producer/Consumer) Consider the following transaction base that defines two processes:

\begin{align*}
\text{produce(}N|\text{List}\text{)} & \leftarrow \text{send(ch, }N\text{) } \otimes \text{produce(List)} \\
\text{produce(}[]\text{)} & \leftarrow \text{send(ch, done)} \\
\text{consume(}\text{Sum, Total}\text{)} & \leftarrow \text{receive(ch, }N\text{) } \otimes \text{consume(}\text{Sum + }N, \text{Total}\text{)} \\
\text{consume(}\text{Total, Total}\text{)} & \leftarrow \text{receive(ch, done)}
\end{align*}

When executed concurrently, the producer sends a list of numbers to the consumer, one number at a time. As the consumer receives the numbers, it adds them together in a running sum (the first argument of \textit{consume}). After the producer has sent all the numbers in the list, it sends the message \textit{done} to the consumer. When the consumer receives the \textit{done} message, it terminates its recursion and returns the total sum (the second argument of \textit{consume}). For instance, the transaction \textit{? - produce([1, 2, 3, 4, 5]) } \mid \text{consume(0, Total)} \textit{causes the producer to send the numbers 1 through 5 to the consumer, while the consumer concurrently receives them, sums them up, and returns Total } = 15. □

Section 2.2 described the predicates for sending and receiving messages via oracles. However, it is worth mentioning that in CTR they can also be defined via run-of-the-mill insert and delete primitives for ground atoms. The three rules below implement a simplified version of these predicates, in which a communication channel is a set of messages, rather than a queue. Intuitively, these rules treat a channel as a "pool" of messages, rather than a "stream." Queues and queue operations are also easily implemented in terms of insert and delete primitives.

\begin{align*}
\text{send(}Ch, \text{Msg}\text{)} & \leftarrow \text{channel.}\text{ins}(Ch, \text{Msg}) & \% \text{Transmit.} \\
\text{peek(}Ch, \text{Msg}\text{)} & \leftarrow \text{channel}(Ch, \text{Msg}) & \% \text{Listen, do not consume.} \\
\text{receive(}Ch, \text{Msg}\text{)} & \leftarrow \circ (\text{channel}(Ch, \text{Msg}) \\
& \quad \circ \text{channel.}\text{del}(Ch, \text{Msg})) & \% \text{Listen and consume.}
\end{align*}

In these rules, communication channels are implemented as a binary database relation, \textit{channel}. Intuitively, \textit{channel}(Ch, Msg) means that channel Ch contains message Msg. Sending a message along a channel amounts to inserting a tuple in the \textit{channel} relation, pecking at a message amounts to retrieving a tuple, and receiving a message amounts to deleting a tuple. Receiving a message requires that the message be in the channel, so tuple deletion is preceded by a query, to make sure that the tuple is there. Note the use of the modal operator \circ, which ensures that checking for a message and consuming it is done atomically, preventing other processes from interposing their actions between the test \textit{channel}(Ch, Msg) and the update \textit{channel.}\textit{del}(Ch, Msg).

3 Model Theory

The semantics of the sequential Transaction Logic is based on sequences of database states, called \textit{paths} [7, 6, 5]. Concurrent Transaction Logic extends this idea to sequences of paths, called \textit{multi-paths}, or \textit{m-paths}. Multi-paths provide the basis for a logical semantics of concurrent conjunction. This section describes the intuitive motivation for multi-paths, and develops them into a formal model theory of CTR.

3.1 Multi-Paths

When a user executes a transaction, the database may change, going from its initial state to some final state. In doing so, the database may pass through any number of intermediate states. For example, the transaction \(\phi = a.\text{ins} \otimes b.\text{ins} \otimes c.\text{ins}\) takes the database from an initial state, D, through the intermediate states \(D + \{a\}\) and \(D + \{a, b\}\), to the final state \(D + \{a, b, c\}\). In sequential Transaction Logic [7, 5], a finite sequence of states is called a \textit{path}, and transactions are true on paths. For example, transaction \(\phi\) is true on the path \(\langle\{\}\{a\}\{a, b\}\{a, b, c\}\rangle\), in which the initial state is the empty database. We say that \(\langle\{\}\{a\}\{a, b\}\{a, b, c\}\rangle\) is an \textit{execution path} of \(\phi\). Execution paths allow us to model a wide range of dynamic constraints [7, 6].

To model concurrent processes, we generalize the notion of path to \textit{multi-path}, or \textit{m-path}. An \textit{m-path} records the execution history of a process. Intuitively, it represents periods of continuous execution, separated by periods of suspended execution (during which other processes may execute). Formally, an \textit{m-path} is a finite sequence of paths, where each constituent path
represents a period of continuous execution. For example, if \( D_1, D_2, \ldots, D_n \) are database states, then \( \langle D_1, D_3, D_5, D_7, D_9, D_{11} \rangle \) is an m-path. If this m-path represents the execution history of process \( \phi \), then the process has three periods of continuous execution. In the first period, \( \phi \) changes the database from \( D_1 \) to \( D_3 \) to \( D_5 \), after which \( \phi \) is suspended and re-awakened when the database is at state \( D_7 \). At this point, \( \phi \) starts its second period of continuous execution, and changes the database from \( D_9 \) to \( D_{11} \). At state \( D_9 \), \( \phi \) is suspended once again and re-awakened when the database reaches state \( D_{11} \) (due to other processes). This begins the third period of \( \phi \)'s execution, which changes the database from \( D_9 \) to \( D_{11} \) to \( D_9 \).

Note that paths are a special case of m-paths, as can be seen from our notation.

**Operations on Multi-Paths.** Concurrent Transaction Logic extends first-order logic with three logical operators: serial conjunction, \( \otimes \), concurrent conjunction, \( | \), and the modality of atonicity, \( @ \). Semantically, these three operators are related to three kinds of operations on m-paths: concatenation, interleaving, and reduction. The rest of this subsection defines these three operations.

**Definition 3.1 (Concatenation)** Suppose that \( \kappa = \langle D_1 \ldots D_k \rangle \) and \( \kappa' = \langle D_k \ldots D_{k+1} \rangle \) are two paths, where \( D_k \) is the last state in \( \kappa \) and also the first state in \( \kappa' \). Then, their concatenation is the path \( \kappa \circ \kappa' = \langle D_1 \ldots D_k \ldots D_{k+1} \rangle \). If \( \tau = \langle \kappa_1, \ldots, \kappa_n \rangle \) and \( \tau' = \langle \kappa'_1, \ldots, \kappa'_m \rangle \) are two m-paths, then their concatenation is the m-path \( \tau \circ \tau' = \langle \kappa_1, \ldots, \kappa_n, \kappa'_1, \ldots, \kappa'_m \rangle \).

The second operation is interleaving. To illustrate, suppose that m-paths \( \langle \kappa_1, \kappa_2 \rangle \) and \( \langle \kappa'_1, \kappa'_2 \rangle \) represent executions of processes \( \phi \) and \( \phi' \), respectively. If we interleave these two m-paths, then we get new m-paths representing interleaved executions of \( \phi \) and \( \phi' \), that is, executions of the composite process \( \phi \| \phi' \). For example, the following four m-paths represent executions of \( \phi \) and \( \phi' \):

- \( \langle \kappa_1, \kappa_1, \kappa_2, \kappa_2 \rangle \)
- \( \langle \kappa_1, \kappa_1, \kappa'_2, \kappa'_2 \rangle \)
- \( \langle \kappa_1, \kappa'_1, \kappa_2, \kappa'_2 \rangle \)
- \( \langle \kappa'_1, \kappa'_1, \kappa_2, \kappa_2 \rangle \)

**Definition 3.2 (Interleaving)** If \( \pi \) and \( \pi_1, \ldots, \pi_n \) are m-paths (i.e., sequences of paths), then \( \pi \) is an interleaving of \( \pi_1, \ldots, \pi_n \) if \( \pi \) can be partitioned into order-preserving subsequences \( C_1, \ldots, C_n \), such that each \( C_i \) is \( \pi_i \). The set of all interleavings of \( \pi_1 \) and \( \pi_2 \) is denoted \( \pi_1 || \pi_2 \).

The final operation on m-paths is reduction. The idea is that if the database state does not change while a process is suspended, then the process can also execute continuously, without any suspension. For instance, if a process can execute along the m-path \( \langle D_1, D_3, D_5 \rangle \), then the process is suspended in state \( D_3 \) and re-awakened in state \( D_5 \). It should therefore be able to execute continuously along the path \( \langle D_1, D_3, D_5 \rangle \). We say that the former m-path reduces to the latter.

**Definition 3.3 (Reduction)** Let \( \tau = \langle \kappa_1, \ldots, \kappa_n \rangle \) be an m-path, where each \( \kappa_i \) is a path. If the paths \( \kappa_i \) and \( \kappa_{i+1} \) can be concatenated, for some \( i \), then we say that \( \tau \) reduces to \( \tau' = \langle \kappa_1, \ldots, \kappa_{i-1}, \kappa_i \circ \kappa_{i+1}, \kappa_{i+2}, \ldots, \kappa_n \rangle \). We also require reduction to be closed under transitivity and reflection.

Observe that reduction is not reversible, since some processes may be specified as atomic. An atomic process must execute continuously, without being suspended and interleaved with other processes. For instance, an atomic process that can execute along \( \langle D_1, D_3, D_5 \rangle \) cannot execute along \( \langle D_1, D_2, D_5 \rangle \). In general, atomic processes can only execute along paths (i.e., without suspension).

### 3.2 Semantics

**\( CTR \) formulas are interpreted by multi-path structures.** A multi-path structure assigns a classical first-order structure to each m-path, specifying which atoms are true on what m-paths. In turn, these atoms determine which formulas are true on what m-paths. Intuitively, a formula that is true on an m-path represents an action that takes place along the m-path. Multi-path structures generalize the path structures of sequential Transaction Logic. Many subtle points about path structures apply equally well to multi-path structures, and the reader is referred to [7, 6, 5] for a thorough discussion. The main novelties of m-path structures are the m-paths themselves, the interleaving operation, and reduction, which account for concurrent and atomic processes.

Recall that \( CTR \) comes with a language, \( \mathcal{L} \), and a pair of oracles, \( O^d \) and \( O^t \), which determine the syntax of formulas and the semantics of databases, as described in Section 2. In the rest of this paper, the language \( \mathcal{L} \) and the oracles are implicit. Also, \( \models' \) denotes satisfaction in classical first-order models.

**Definition 3.4 (Multi-Path Structures)** Let \( \mathcal{L} \) be a language of \( CTR \) with the set of function symbols \( \mathcal{F} \). A multi-path structure (abbr. m-path structure) \( \mathbb{M} \) over \( \mathcal{L} \) is a triple \( \langle U, I_F, I_{\text{path}} \rangle \), where:

- \( U \) is a set, called the domain of \( \mathbb{M} \).
• $I_{F}$ is an interpretation of function symbols in $L$. It assigns a function $U^n \to U$ to every $n$-ary function symbol in $F$.

Given $U$ and $I_{F}$, let $\text{Struct}(U, I_{F})$ denote the set of all classical first-order semantic structures over $L$ of the form $(U, I_{F}, I_{P})$, where $U$ is the domain of the structure, $I_{F}$ is a mapping that interprets predicate symbols in $P$ by relations on $U$, and $U$ and $I_{F}$ are the same as in $M$.

• $I_{path}$ is a total mapping from the m-paths in $L$ to the semantic structures in $\text{Struct}(U, I_{F})$. $I_{path}$ is subject to the following restrictions:

- Conformance with m-path reduction: If an m-path $\pi_1$ reduces to $\pi_2$, then $I_{path}(\pi_1) = \models \alpha$ implies $I_{path}(\pi_2) = \models \alpha$, for every atomic formula $\alpha$ (i.e., if $\alpha$ can execute along $\pi_1$, then it can execute along $\pi_2$).

- Compliance with the data oracle: $I_{path}(\langle D \rangle) = \models \phi$ for every formula $\phi \in O^d(D)$.

- Compliance with the transition oracle: $I_{path}(\langle D_1 D_2 \rangle) = \models b$ for every atomic formula $b \in O^d(D_1, D_2)$.

As in classical logic, a variable assignment, $\nu$, is a mapping $V \to U$ that takes variables as input and returns domain elements as output. We extend the mapping from variables to terms in the usual way.

**Definition 3.5 (Satisfaction)** Let $M = (U, I_F, I_{path})$ be an m-path structure, let $\pi$ be an arbitrary m-path, and let $\nu$ be a variable assignment. Then,

1. **Base Case:** $M, \pi \models \nu p(t_1, \ldots, t_n)$ iff $I_{path}(\pi) \models \nu p(t_1, \ldots, t_n)$, for any atomic formula $p(t_1, \ldots, t_n)$.

2. **Negation:** $M, \pi \models \neg \phi$ iff it is not the case that $M, \pi \models \phi$.

3. **"Classical" Conjunction:** $M, \pi \models \nu \phi \land \psi$ iff $M, \pi \models \nu \phi$ and $M, \pi \models \nu \psi$.

4. **Serial Conjunction:** $M, \pi \models \nu \phi \lor \psi$ iff $M, \pi_1 \models \nu \phi$ and $M, \pi_2 \models \nu \psi$ for some m-paths $\pi_1, \pi_2$ whose concatenation $\pi_1 \cdot \pi_2$ reduces to $\pi$.

5. **Concurrent Conjunction:** $M, \pi \models \nu \phi \land \psi$ iff $M, \pi_1 \models \nu \phi$ and $M, \pi_2 \models \nu \psi$ for some m-paths $\pi_1, \pi_2$ with an interleaving in $\pi_1 \parallel \pi_2$ that reduces to $\pi$.

6. **Universal Quantification:** $M, \pi \models \nu \forall X. \phi$ iff $M, \pi \models \nu \phi$ for every variable assignment $\mu$ that agrees with $\nu$ everywhere except on $X$.

7. **Atomic Processes:** $M, \pi \models \nu \otimes \phi$ iff $M, \pi \models \nu \phi$ and $\pi$ is a path (not a general m-path).

As in classical logic, the mention of variable assignment can be omitted for sentences, i.e., for formulas with no free variables. From now on, we will deal only with sentences, unless explicitly stated otherwise. If $M, \pi \models \phi$, then we say that $\phi$ is satisfied (or is true) on m-path $\pi$ in structure $M$.

It can be seen from the definitions that on paths of length 1, the connectives $\otimes, \parallel, \land$ all reduce to the usual conjunction of classical predicate logic. Thus, the “classical,” serial, and concurrent conjunctions in CTR extend the usual conjunction in classical logic from states to execution paths, albeit in three different ways. The following lemma states a basic property of satisfaction on m-paths. It is proved by a straightforward induction on the structure of $\psi$.

**Lemma 3.1** If m-path $\pi_1$ reduces to $\pi_2$, then for any m-path structure $M$ and transaction formula $\psi$, $M, \pi_1 \models \psi$ then $M, \pi_2 \models \psi$.

**Definition 3.6 (Models)** An m-path structure $M$ is a path-model (or simply a model) of a transaction formula $\phi$, written $M \models \phi$, iff $M, \pi \models \phi$ for every m-path $\pi$. An m-path structure is a model of a set of formulas iff it is a model of every formula in the set.

### 3.3 Execution as Entailment

A CTR program has two distinct parts: a transaction base $P$ and an initial database state $D$. Recall that the database is a set of data items, and the transaction base is a finite set of transaction formulas. Of these two parts, only the database is updatable. The transaction base is immutable and specifies procedures for updating the database and answering queries. The transaction base will normally be composed of formulas containing the new connectives, $\otimes, \parallel$, and $\otimes$, although classical first-order formulas are also allowed. With this in mind, we are ready to define executional entailment, a concept that provides a logical account of transaction execution.
Definition 3.7 (Execution Entailment) Let $P$ be a transaction base. If $\phi$ is a transaction formula and $D_0, D_1, \ldots, D_n$ is a sequence of database states, then the statement

$$P, D_0, D_1, \ldots, D_n \models \phi$$

(1)

is true iff $M, (D_0, D_1, \ldots, D_n) \models \phi$, for every model $M$ of $P$. (Since the oracles are parameters to $CTR$, the set of all states is fixed.) Related to this is the statement

$$P, D_0 \ldots \models \phi$$

(2)

which are true iff Statement (1) is true for some sequence of database states $D_0, D_1, \ldots, D_n$.

Intuitively, Statement (1) says that a successful execution of transaction $\phi$ can change the database from state $D_0$ to $D_1, \ldots$ to $D_n$. Formally, it means that in every model of $P$, the $m$-path $(D_0, D_1, \ldots, D_n)$ satisfies formula $\phi$. The statement is read as follows: "Under the transaction base $P$, the transaction $\phi$ may transform database $D_0$ into database $D_n$ by passing through intermediate states $D_1, \ldots, D_{n-1}$.''

Observe that executional entailment is defined over paths, not over arbitrary $m$-paths. This is because executional entailment describes the behavior of a complete system of transactions, which behaves like an atomic transaction since its execution is not interleaved with anything else. Intuitively, a more general $m$-path with "gaps" represents the execution of an incomplete system of transactions, since the gaps must be "filled in" by the execution of other, unspecified transactions.

Normally, users issuing transactions know only the initial database state $D_0$, so defining transaction execution via (1) is not always appropriate. This situation is captured by Statement (2), which omits the intermediate and the final database states. Informally, Statement (2) says that transaction $\phi$ can execute successfully starting from database $D_0$. Formally, this statement is read as follows: "Under the transaction base $P$, the transaction $\phi$ succeeds from database $D_0$.

When the context is clear, we simply say that transaction $\phi$ succeeds. Likewise, when statement (2) is not true, we say that transaction $\phi$ fails. In Section 4, we present an inference system that actually finds a database sequence, $D_1, \ldots, D_n$, that satisfies Statement (1) whenever a transaction succeeds.

4 Proof Theory

Like classical logic, $CTR$ has a "Horn" version, which has both a procedural and a declarative semantics. It is this property that allows a user to program transactions within the logic. This section defines the Horn subset of $CTR$ and develops an SLD-style proof theory that is both sound and complete. Unlike classical logic programming, the proof theory presented here computes new database states as well as query answers. In this sense, it is similar to the proof theory of sequential Transaction Logic. However, the latter proof theory accounts only for sequential processes, while the proof theory developed here accounts for concurrent and atomic processes as well. This leads to the notion of hot components, defined as those subprocesses that are ready to execute.

In the Horn fragment of $CTR$, database states are represented by a Horn oracle, as defined in Section 2.2. In addition, the transaction base $P$ must satisfy certain conditions. The first condition is based on the idea of concurrent serial goal, defined below, which generalizes the notion of conjunctive query in classical database theory. We say that $b \leftarrow \phi$ is a concurrent Horn rule if $b$ is an atomic formula and $\phi$ is a concurrent serial goal. All examples in this paper use concurrent Horn rules. Finally, we say that the combination of a transaction base $P$ and a Horn data oracle $O(D)$ is concurrent Horn if $P$ is a set of concurrent Horn rules satisfying the following independence condition: For every database state $D_0$, predicate symbols occurring in rule-heads in $P$ do not occur in rule-bodies in $O(D)$. Intuitively, the independence condition means that the database does not define predicates in terms of transactions. Thus, the rule $a \leftarrow b$ cannot be in the database if the rule $b \leftarrow c$ is in the transaction base. Observe that all relational databases satisfy the independence condition, since the data oracle returns only a set of atoms.

Definition 4.1 (Concurrent Serial Goal) A concurrent serial goal is any formula of the form:

- An atomic formula; or
- $\phi_1 \otimes \ldots \otimes \phi_k$, where each $\phi_i$ is a concurrent serial goal, and $k \geq 0$; or
- $\phi_1 \mid \ldots \mid \phi_k$, where each $\phi_i$ is a concurrent serial goal, and $k \geq 0$; or
- $\otimes \phi$, where $\phi$ is a concurrent serial goal.
4.1 Inference System $\mathcal{C}$

This section develops an inference system for verifying $\mathbf{P}, \mathbf{D}_0 \vdash \psi$. Informally, this statement says that transaction $\psi$ can successfully execute starting from state $\mathbf{D}_0$. The inference succeeds if it finds an execution path for the transaction $\psi$, that is, a sequence of databases $\mathbf{D}_1, \ldots, \mathbf{D}_n$ such that $\mathbf{P}, \mathbf{D}_0, \mathbf{D}_1, \ldots, \mathbf{D}_n \vdash \psi$. We refer to the inference system of this section as $\mathcal{C}$.

The inference rules of $\mathcal{C}$ focus on the left end of a transaction. Intuitively, this corresponds to the left-to-right execution of serial transactions. For instance, in the transaction $a_1 \otimes a_2 \otimes \ldots \otimes a_k$, the subtransaction $a_1$ executes first, then $a_2$, then $a_3$, and so on until $a_k$ executes. Because of concurrency, there may be many subtransactions ready for execution at any given time. For instance, in the transaction $a_1 \otimes a_2 \otimes a_3$, any of the subtransactions $a_1, a_2, a_3$ can start executing first. The next definition formalizes this idea. It defines the set of subformulas that are ready for execution, which we refer to as “hot” components. Figure 1 illustrates the idea.

**Definition 4.2 (Hot Components)** Let $\phi$ be a concurrent serial goal. Its set of hot components, written $\text{hot}(\phi)$, is defined recursively as follows:

- $\text{hot}(\emptyset) = \{\emptyset\}$, where $\emptyset$ is the empty goal;
- $\text{hot}(b) = \{b\}$, if $b$ is an atomic formula;
- $\text{hot}(\phi_1 \otimes \ldots \otimes \phi_k) = \text{hot}(\phi_1)$;
- $\text{hot}(\phi_1 \otimes \ldots \otimes \phi_k) = \text{hot}(\phi_1) \cup \ldots \cup \text{hot}(\phi_k)$;
- $\text{hot}(\square \phi) = \{\square \phi\}$.

Just as databases and logic programs assume that queries are existentially quantified, we shall assume that processes are existentially quantified. We thus introduce the notion of an existential goal, which is a formula of the form $\exists \overline{X} \phi$, where $\phi$ is a concurrent serial goal. For convenience, we shall often drop the variable list $\overline{X}$ and simply write $(\exists) \phi$.

**Definition 4.3 (Inference in $\mathcal{C}$)** If $\mathbf{P}$ is a concurrent Horn transaction base, then $\mathcal{C}$ is the following system of axioms and inference rules, where $\mathbf{D}$ is any legal database state.

**Axioms:** $\mathbf{P}, \mathbf{D} \vdash \emptyset$, for any $\mathbf{D}$.

**Inference Rules:** In Rules 1–4 below, $\sigma$ is a substitution, $\psi$ and $\psi'$ are concurrent serial conjunctions, and $\mathbf{a}$ is an atomic formula in $\text{hot}(\psi)$.

1. **Applying transaction definitions:** Let $b \mapsto \beta$ be a rule in $\mathbf{P}$, and assume that its variables have been renamed so that none are shared with $\psi$. If $a$ and $b$ unify with mgu $\sigma$ then

   \[
   \frac{\mathbf{P}, \mathbf{D} \vdash (\exists) \psi' \sigma}{\mathbf{P}', \mathbf{D} \vdash (\exists) \psi}
   \]

   where $\psi'$ is obtained from $\psi$ by replacing a hot occurrence of $a$ by $\beta$.
   For instance, if $\psi = e \mid a \mid d$ then $\psi' = e \mid \beta \mid d$.

2. **Querying the database:** If $\mathcal{O}(\mathbf{D}) \models^e (\exists) a \sigma$, and $a \sigma$ and $\psi' \sigma$ share no variables, then

   \[
   \frac{\mathbf{P}, \mathbf{D} \vdash (\exists) \psi' \sigma}{\mathbf{P}', \mathbf{D} \vdash (\exists) \psi}
   \]

   where $\psi'$ is obtained from $\psi$ by deleting a hot occurrence of $a$.
   For instance, if $\psi = e \mid a \mid d$ then $\psi' = e \mid d$.

3. **Executing elementary updates:** If $\mathcal{O}(\mathbf{D}_1, \mathbf{D}_2) \models^e (\exists) a \sigma$ and $a \sigma$ and $\psi' \sigma$ share no variables, then

   \[
   \frac{\mathbf{P}_1, \mathbf{D}_2 \vdash (\exists) \psi' \sigma}{\mathbf{P}_1, \mathbf{D}_1 \vdash (\exists) \psi}
   \]

   where $\psi'$ is obtained from $\psi$ by deleting a hot occurrence of $a$.
   For instance, if $\psi = e \mid a \mid d$ then $\psi' = e \mid d$. 

\[
\begin{array}{|c|c|}
\hline
\text{Formula} & \text{Hot Components} \\
\hline
a \otimes b \otimes c & \{a, b, c\} \\
(a \otimes b) \otimes (c \otimes d) & \{a, b, c, d\} \\
(a \otimes b) \otimes (c \otimes d) & \{a, b, c\} \\
\hline
\end{array}
\]
Figure 2: An Inference in $\exists^C$

<table>
<thead>
<tr>
<th>Sequent</th>
<th>Int. Rule</th>
<th>Hot Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1 \vdash \alpha \land q$</td>
<td>1</td>
<td>${q, \alpha}$</td>
</tr>
<tr>
<td>$P_2 \vdash \beta$</td>
<td>2</td>
<td>${\text{c.ins}, q}$</td>
</tr>
<tr>
<td>$P_3 \vdash \gamma$</td>
<td>3</td>
<td>${\text{c.ins, e.ins}}$</td>
</tr>
<tr>
<td>$P_4 \vdash \delta$</td>
<td>4</td>
<td>${\text{d.ins, e.ins}}$</td>
</tr>
<tr>
<td>$P_5 \vdash \epsilon$</td>
<td>5</td>
<td>${\text{d.ins, f.ins}}$</td>
</tr>
<tr>
<td>$P_6 \vdash \zeta$</td>
<td>6</td>
<td>${\text{d.ins}}$</td>
</tr>
<tr>
<td>$P_7 \vdash \eta$</td>
<td>7</td>
<td>${}$</td>
</tr>
</tbody>
</table>

4. **Executing atomic transactions**: If $\circ \alpha$ is a hot component in $\psi$ then

$$P, D \vdash \beta \land (\exists \psi' \land (\circ \alpha \land \psi))$$

$$P, D \vdash \beta \land (\exists \psi')$$

where $\psi'$ is obtained from $\psi$ by deleting a hot occurrence of $\circ \alpha$.

For instance, if $\psi = c \parallel (\circ \alpha) \parallel d$ then $\psi' = (c \parallel d)$.

This system manipulates expressions of the form $P, D \vdash \beta$, called *sequents*. The informal meaning of such a sequent is that the transaction $(\exists \psi)$ can succeed from $D$, i.e., it can execute on a path starting at database $D$. Each inference rule consists of two sequents, one above the other, and has the following interpretation: If the upper sequent can be inferred, then the lower sequent can also be inferred. As in classical resolution, any instance of an answer-substitution is a valid answer to a query.

To understand inference system $\exists^C$, first note that the axioms describe the empty transaction, "()". By definition, this transaction does nothing and always succeeds. That is, if the user issues the command ? - ( ), then the database simply remains in its current state. The axioms formalize this behavior. The four inference rules describe more complex transactions. To understand these rules, it is convenient to temporarily ignore the unifier, $\sigma$, and to assume that $a$ is identical to $b$. With this in mind, we can interpret the rules as follows:

1. **Inference rule 1** deals with defined transactions. It assumes that $b$ is defined by $\beta$, and $\beta$ is a subtransaction of $\psi'$. The rule says that if transaction $\psi'$ succeeds from database $D$, then so does $\psi$. Intuitively, this rule replaces a subroutine definition, $\beta$, by its calling sequence, $b$.

2. **Inference rule 2** deals with tests (i.e., queries) that do not cause state changes. It assumes that test $b$ is true at state $D$. The rule says that if transaction $\psi'$ succeeds from $D$, then so does $\psi$. Intuitively, $b$ is a pre-condition that is satisfied by $D$, so it can be attached to the front of $\psi'$.

3. **Inference rule 3** deals with elementary updates. It assumes that update $b$ transforms the database from state $D_1$ to state $D_2$. The rule says that if transaction $\psi'$ succeeds from $D_2$, then transaction $\psi$ succeeds from $D_1$. Intuitively, $b$ is attached to the front of $\psi'$, so that the resulting transaction starts from $D_1$ instead of $D_2$.

4. **Rule 4** deals with atomic subtransactions. It assumes that subtransaction $\alpha$ is ready to execute, and that it must execute atomically. To achieve atomicity, the rule extracts $\alpha$ from the main transaction, $\psi$; then it executes $\alpha$ to completion; and then it executes the rest of transaction $\psi$, which we have denoted $\psi'$. This is expressed by the formula $\alpha \land \psi'$. Here $\alpha$ executes atomically since it is not interleaved with anything.

**Example 4.4 (Deduction)** Suppose the data oracle is relational and the transition oracle inserts propositional atoms into the database. Suppose also that the transaction base $P$ contains the following two rules:

$$p \leftarrow \text{c.ins} \land \text{d.ins} \quad q \leftarrow \text{e.ins} \land \text{f.ins}$$

Then the formula $p \mid q$ represents a transaction in which the atoms $c, d, e, f$ are inserted into the database, where $c$ is inserted before $d$ and $e$ before $f$. This transaction can be executed several ways. Figure 2 illustrates one possibility. It shows a derivation of the sequent $P, \{\} \vdash p \mid q$. Each sequent in the table is derived from the one below by an inference rule. The deduction succeeds because the bottom-most sequent is an axiom. When carried out top-down, the deduction corresponds to an execution of the transactio $p \mid q$ in which atoms are inserted into the empty database in the order $c, e, f, d$.

**Theorem 4.1 (Soundness and Completeness of $\exists^C$)** If $P$ is a concurrent Horn transaction base, and $\psi$ is a concurrent serial goal, then the executional entailment $P, D \vdash (\exists \psi)$ holds if and only if there is a deduction in $\exists^C$ of the sequent $P, D \vdash (\exists \psi)$.

---

*Model theoretically, "( )" is a transaction that is true on every m-path of the form (D), i.e., on any m-path corresponding to a single database [7, 8].*
Having developed the inference system, we must remind ourselves that our original goal was not so much proving statements of the form \( \mathsf{P, D} \models (3) \phi \), but rather of the form \( \mathsf{P, D}_0, \ldots, D_n \models (3) \phi \), where \( D_0 \) is the database state at the time the user issues the transaction \(? \models (3) \phi \). Note that the intermediate states, \( D_1, \ldots, D_{n-1} \), and the final state, \( D_n \), are unknown at this time. An important task for the inference system is to compute these states. A general notion of deduction is not tight enough to do this conveniently, since general deduction may record the execution of many unrelated transactions, mixed up in a haphazard way. Since we are interested in the execution of a particular transaction, we introduce the more specialized notion of executional deduction, which—without sacrificing completeness—defines a narrower range of deductions. The notion of executional deduction needed here is exactly the same as that developed for sequential Transaction Logic in [7, 5]. It also leads naturally to a proof-theoretic notion of execution path. It remains only to show that executional deduction in concurrent Transaction Logic is sound and complete for the model theory of Section 3. This is established by the following theorem.

**Theorem 4.2 (Executional Soundness and Completeness of \( \mathcal{C} \))** Let \( \mathsf{P} \) be a concurrent Horn transaction base, and let \( \phi \) be a concurrent serial goal. There is an executional deduction of \( (3) \phi \) whose execution path is \( D_0 D_1 \ldots D_n \) iff the following is true:

\[
\mathsf{P, D}_0, D_1 \ldots, D_n \models (3) \phi.
\]

## 5 Expressive Power

The ability to express the send and receive primitives using the modal operator \( \odot \) provides for general communication and synchronization among \( \mathsf{CTR} \) processes. A process can send a message and either choose to synchronize with the receiver immediately or go on doing its business, possibly synchronizing later. In other words, both synchronous and asynchronous communication are supported. To synchronize with another process, a process calls \( \text{receive}(\mathsf{Ch}, \mathsf{Msg}) \), where \( \mathsf{Ch} \) and \( \mathsf{Msg} \) are (possibly non-ground) terms, as illustrated in Example 2.2. Such a process cannot advance beyond this call until a channel that unifies with \( \mathsf{Ch} \) has a message that unifies with \( \mathsf{Msg} \). In that sense, \( \mathsf{CTR} \) supports pattern-directed communication. Patterns (which in our case are function terms representing channels) can be arranged in various ways to achieve point-to-point, broadcast, blackboard, and other forms of communication, with bounded or unbounded buffers.

**Dynamic Communication Topology:** As in the \( \pi \)-calculus [19], \( \mathsf{CTR} \) processes can send channel names to each other, through which they can communicate later, thereby changing the communication topology. To illustrate, the program below simulates a simple server that responds to client requests. Intuitively, the predicate \( \text{client(Id)} \) represents a client process with identifier \( \mathsf{Id} \). The predicate \( \text{server(N)} \) represents a server process that can respond to \( \mathsf{N} \) client requests before expiring. The client and server processes can be started in any number of ways. For example, to create three clients and a server that can respond to three requests, the system administrator could issue the following command:

\[
? - \text{server(3) \mid client(c1) \mid client(c2) \mid client(c3)}.
\]

where the constants \( c1, c2, c3 \) are client identifiers. The immediate effect of this command is to create four concurrent processes: one server process, and three client processes. As the clients send requests to the server, additional concurrent processes will be created by the server.

\[
\begin{align*}
\text{server(0)} & \leftarrow \\
\text{server(N)} & \leftarrow \text{receive(servConnect, Ch) \odot [servClient(Ch) \mid server(N - 1)]} \\
\text{servClient(Ch)} & \leftarrow \text{receive(Ch, Request) \odot doIt(Request, Result) \odot send(Ch, Result)} \\
\text{client(Id)} & \leftarrow \text{newChan(Ch) \odot \ldots \odot send(servConnect, Ch) \odot clientWork(Id, Ch)} \\
\text{clientWork(Id, Ch)} & \leftarrow \text{send(Ch, Req) \odot \ldots \odot receive(Ch, Result) \odot \ldots \odot delChan(Ch)}
\end{align*}
\]

Here, \( \text{servConnect} \) is the name of a public communication channel. The predicate \( \text{newChan(Ch)} \) is an atomic process that creates a private channel and returns its name, \( \mathsf{Ch} \). The predicate \( \text{delChan(Ch)} \) is an atomic process that destroys channel \( \mathsf{Ch} \). \( \text{newChan} \) and \( \text{delChan} \) are easily defined via the transition oracle or the transaction base [7].

A client process \( \text{client(Id)} \) first generates a new channel, \( \mathsf{Ch} \). It then connects to the server via the public channel, passing it the new channel name. The server then spawns a subprocess \( \text{servClient(Ch)} \) to deal with the client. Future communication between the client and this subprocess takes place along the new channel, \( \mathsf{Ch} \). This communication has a simple form: the client sends a request \( \text{Req} \) to the server subprocess, which carries out the request, and sends the result back to the client. Finally, the client destroys its private channel and terminates.
Passing Process Names: In addition to sending channel names between processes, in CTR, one can send process names between processes. One way to do this is to give each process an id encoded as a function term, like the client id's used above. Process names can then be sent and received like other messages, and executed like other processes. Another way to do this is to extend CTR in the direction of HiLog [9], a well-known higher-order extension of classical logic.

In a nutshell, HiLog allows variables over functions, predicate symbols, and even over atomic formulas. Moreover, the distinction between atomic formulas and terms is completely erased, and arbitrary (even non-ground) terms can serve as predicate names in HiLog, which provides a convenient way of defining generic logical procedures [9]. For instance, \( A(X, Y, Z) \) is a well-formed term in HiLog. As a concrete example, the rules below define a predicate \( \text{fact}(N)(A) \) that computes the factorial function. The definition is pretty much classical except that \( \text{fact}(N) \) is treated as a parameterized predicate, with the parameter serving as input. Thus, \( \text{fact}(20)(A) \) means compute 20! and return the result in A. The reason for using HiLog here is that it lets us transmit and execute processes without knowing their precise calling sequence.

To illustrate these ideas, consider the two processes \( \text{proc1} \) and \( \text{proc2} \) defined below. To see how they work, suppose the user issues the command \( ?- \text{proc1}(\text{ch1}, \text{fact}(20), A) \mid \text{proc2}(\text{ch1}) \). First, the process \( \text{proc1} \) sends the term \( \text{fact}(20) \) out along channel \( \text{ch1} \). Process \( \text{proc2} \) then receives \( \text{fact}(20) \), interprets it as a process, and executes it. Finally, \( \text{proc2} \) sends the answer out along channel \( \text{ch1} \), whence \( \text{proc1} \) receives the answer and returns it to the user.

\[
\begin{align*}
\text{proc1}(\text{Ch}, \text{Process}, \text{Ans}) & \leftarrow \text{send}(\text{Ch}, \text{Process}) \otimes \text{receive}(\text{Ch}, \text{Ans}) \\
\text{proc2}(\text{Ch}) & \leftarrow \text{receive}(\text{Ch}, \text{Process}) \otimes \text{Process}(\text{Ans}) \otimes \text{send}(\text{Ch}, \text{Ans}) \\
\text{fact}(0)(1) & \leftarrow \text{fact}(N)(N \times A) \leftarrow \text{fact}(N - 1)(A)
\end{align*}
\]

Guarded Clauses: Finally, a remark on the relationship between CTR and concurrent logic programming (CLP) languages [24] is in order. Since the semantics of these languages has eluded capture in logic, we will not pretend that CTR can simulate these languages faithfully. However, some analogies can be made. For instance, CLP languages commonly use the idea of rules with guarded bodies, which can have the following form:

\[
\text{head} \leftarrow g_1, \ldots, g_n \mid a_1, \ldots, a_m
\]

When \( \text{head} \) unifies with the goal, the guards \( g_1, \ldots, g_n \) are evaluated. If they all succeed, then the subgoals \( a_1, \ldots, a_m \) are executed concurrently. An important point here is that if one of the subgoals \( a_i \) fails, then \( \text{head} \) also fails, even though another clause for \( \text{head} \) —had it been chosen instead of (4)—could have succeeded. The CTR analogue of (4) is:

\[
\text{head} \leftarrow g_1 \otimes \ldots \otimes g_n \otimes (a_1 | \ldots | a_m)
\]

A crucial difference with guarded rules is that CTR does not rely on committed choice, which is so inherent to CLP languages. Thus, if some \( a_i \) fails, then another clause for \( \text{head} \) will be tried.

The importance of committed choice in CLP languages is that it helps control non-determinism, leading to greater efficiency. However, committed choice has been criticized for its distinctly non-logical semantics that may cause a system to commit to a clause that would later fail, even though another clause would have succeeded. In contrast, CTR offers a different paradigm, one with clean, logical model and proof theories and several ways of controlling non-determinism via synchronization. Non-determinism has entirely different nature here ("don't know" rather than "don't care" [24]), and it is deeply rooted in the model theory.

6 Conclusions and Discussion

We presented Concurrent Transaction Logic (CTR), a logic that can declaratively specify and procedurally execute concurrent communicating database processes involving queries, updates, or combinations of both. It is thus a high-level deductive language for programming database applications, a language with a completely logical semantics. The semantics emphasizes the combination of elementary database operations into complex processes. The elementary operations themselves are not built into the semantics of CTR, but rather play the role of a parameter to the logic. In this paper, we focused on the concurrent Horn subset of CTR and developed its model theory and a sound and complete proof theory.

CTR is not Yet-Another-Logic, unrelated and isolated from other extensions. It is an idea that is orthogonal to several other recent proposals, such as F-logic [13] (structural object-orientation), HiLog [9] (higher-order logic programming), and Annotated Logic [14] (reasoning with uncertainty), and it can be easily integrated with them to endow these static formalisms with the ability to capture database dynamics in a clean, logical fashion (cf., e.g., [12]).
The communication paradigm within CTR is inspired by the π-calculus [19]. However, CTR is a programming logic, while π-calculus is an algebra used for specifying and verifying finite-state concurrent systems (which databases and logic programs are not). Although there is growing interest in designing programming languages based on π-calculus (e.g., PICT [22]), the application domain of such languages seems very different from CTR. These languages have a functional flavor, and their ability to express data-driven non-determinism is limited. Once a process is committed to a certain execution path, there is no possibility for failure. In general, it is hard to specify pre-conditions and post-conditions in π-calculus, and search-related problems, such as those arising in databases and AI are difficult to program. Compared to π-calculus, concurrency in CTR is more flexible in some respects, and more limited in others. For instance, CTR supports both synchronous and asynchronous communication, while the π-calculus requires a hand-shake. Like the π-calculus, CTR can send and receive messages and channels, and it can reconfigure the communication topology dynamically. To a large extent, CTR processes can create private communication channels, à la π-calculus. With a simple extension in the direction of HiLog [9], CTR can pass transactions between processes for remote execution.

In a recent work, Miller [18] has shown that most of the π-calculus can be encoded in Linear Logic [10]. The reduction process of the π-calculus is simulated via the proof theory of Linear Logic. However, the semantics of Linear Logic does not give direct meaning to execution and communication, unlike CTR. Also, the programming paradigm that might arise from such an encoding seems to imitate the behavior of π-calculus, which is quite different from the programming style of CTR, which draws on deductive databases and logic programming.

Linear Objects is another concurrent formalism based on Linear Logic [1]. Processes are represented via logic formulas and their execution corresponds to branches in a proof tree. The semantics is provided via a mapping into Linear Logic, although, strictly speaking, this does not yet provide a model-theoretic account of concurrency. Furthermore, although processes can communicate, there does not seem to be an obvious way for one process to change the database and for others to query the changes (or to have different views of the changes). There is also no programming language for specifying how processes evolve. Instead, one must list all the operations performed by a process (and its sub-processes) before execution begins.

Another related formalism, rewriting logic [16], is a general framework for specifying executable concurrent systems. Rewriting logic serves two purposes: as a general framework within which to compare different concurrent formalisms, and as a workbench for designing languages for programming concurrent systems. In the first capacity, we believe that an embedding of CTR into rewriting logic may prove useful for clarifying the relationship between CTR and other concurrent formalisms. In the second capacity, rewriting logic has been used to design languages for object-oriented programming [17], and equational programming [17]. However, the programming paradigm of CTR is fundamentally different from these other languages.

Some of the earliest attempts at adding concurrency to logic programming were PARLOG, Concurrent Prolog, GHC, and related languages (see [24] for a survey). We discussed possible connections between CTR and concurrent logic programming earlier in this paper. Although concurrent logic programming languages lack model-theoretic semantics, the programming paradigm promoted by these languages is related to rewriting logic and linear objects in the sense that once the flow of control commits to a certain action, this action never backtracks; this style is quite unlike the one promoted by CTR.

Finally, a comparison of CTR with Concurrent Dynamic Logic (CDL) [21, 20] is in order. There are two versions of CDL. The version developed in [21] is very different from CTR. It is modeled on the kind of concurrency found in alternating Turing machines, which does not allow for communication between concurrent processes. A deductive-database analogue of this version of CDL is Hypothetical Datalog [4], in which hypothetical databases represent the states of the various (non-communicating) concurrent processes in an alternating computation. The version of CDL developed in [20] does allow for communication, but only after adding considerable complexity to the semantics.

In both versions of CDL, the meaning and intent of dynamic formulas is fundamentally different from that of transaction formulas in CTR. CDL was intended to reason about what is true during program execution, while CTR was designed to actually execute declaratively specified procedures. This difference in the intent is reflected in the syntax. For instance, CDL uses a separate alphabet to represent actions, and a set of modal operators to reason about them. Thus, unlike CTR, CDL processes are not represented as propositions. In particular, processes are not logical formulas, but rather are terms used in constructing modal operators. One consequence is that only elementary actions have names. Composite actions cannot be named, and thus the logic lacks a subroutine facility. Another difference between CTR and CDL is in the nature of states. In CTR, the concept of a state immediately leads to the idea of data and transition oracles. In contrast, CDL worries about internal states of executing programs, while the notion of a database state is entirely missing. It is also worth noting that these statements equally apply to another related logic, Process Logic [11], although we are not aware of any extensions of Process Logic that allow concurrency and communication.
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