Abstract

This work introduces the notion of multi-version conflict notion.

1. Introduction

In recent years, Software Transactional Memory systems (STMs) [2][3][13] have garnered significant interest as an elegant alternative for addressing concurrency issues in memory. STMs take optimistic approach. Multiple transactions are allowed to execute concurrently. On completion, each transaction is validated and if any inconsistency is observed it is aborted. Otherwise it is allowed to commit.

An important requirement of STM system is to ensure that transactions do not abort unnecessarily. This referred to as the progress condition. It would be ideal to abort a transaction only if committing it violates the correctness-criterion.

With the increase in concurrency, more transactions may conflict and abort, especially in presence many long-running transactions which can have a very bad impact on performance [3]. Perelman et al [12] observe that read-only transactions play a significant role in various types of applications. But long read-only transactions could be aborted multiple times in many of the current STM systems. The objects accessed by the read and write operations are called as transaction objects. For the sake of simplicity, we assume that the values written by all the transactions are unique.

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For two transactions T1 and T2 a transaction T1 < T2 if T1 starts before T2 or T1 finishes before T2. T1 ≡ T2 if both T1 and T2 start at the same time and complete at the same time. TXS(H) is the set of transactions that update H. TXS(H) is a partial order with TXS(H) ≤ TXS(H). TXS(H) is a partial order with TXS(H) ≤ TXS(H).

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2. System Model and Preliminaries

The notions and definitions described in this section follow the definitions of [9]. We assume a system of n processes, p1, . . . , pn, that access a collection of objects via atomic transactions. The processes are provided with four transactional operations: the write(x, v) operation that updates object x with value v, the read(x) operation that returns a value read in x, tryC() that tries to commit the transaction and returns commit (c for short) or abort (a for short), and tryA() that aborts the transaction and returns A.

Operations write, read and tryC() may return a, in which case we say that the operations forcibly abort. Otherwise, we say that the operation has successfully executed. Each operation is equipped with a unique transaction identifier. A transaction Tk starts with the first operation and completes when any of its operations returns a or c. Abort and commit operations are called terminal operations.

For a transaction Tk, we denote all its read operations as Rset(Tk) and write operations Wset(Tk). Collectively, we denote all the operations of a transaction Ti as evts(Ti).

Histories. A history is a sequence of events, i.e., a sequence of invocations and responses of transactional operations. The collection of events is denoted as evts(H). For simplicity, we only consider sequential histories here: the invocation of each transactional operation is immediately followed by a matching response. Therefore, we treat each transactional operation as one atomic event, and let <$H denote the total order on the transactional operations incurred by H. With this assumption the only relevant events of a transaction Tk are of the types: rTk(x, v), wTk(x, v), w0(x, v, A), tryCk(C) (or cA for short), tryCk(A), tryAk(A) (or aA for short). We identify a history H as tuple (evts(H), <$H).

Let HT denote the history consisting of events of T in H, and H[p denote the history consisting of events of pk in H. We only consider well-formed histories here, i.e., (1) each HT consists of a read-only prefix (consisting of read operations only), followed by a write-only part (consisting of write operations only), possibly completed with a tryC or tryA operator[7] and (2) each H[p consists of a sequence of transactions, where no new transaction begins before the last transaction completes (commits or aborts).

We assume that every history has an initial committed transaction Tk that initializes all the data-objects with 0. The set of transactions that appear in H is denoted by txns(H). The set of committed (resp., aborted) transactions in H is denoted by committed(H) (resp., aborted(H)). The set of incomplete (or live) transactions in H is denoted by incomplete(H) (incomplete(H) = txns(H) − committed(H) − aborted(H)). For a history H, we construct the completion of H, denoted H, by inserting aA immediately after the last event of every transaction Tk ∈ incomplete(H). Transaction orders. For two transactions Tk, Tm ∈ txns(H), we say that Tk precedes Tm in the real-time order of H, denote Tk aRT Tm, if Tk is complete in H and the last event of Tk precedes the first event of Tm in H. If neither Tk aRT Tm nor

A This restriction brings no loss of generality [10].
T_m \prec_H^RT T_k$, then $T_k$ and $T_m$ overlap in $H$. A history $H$ is $t$-sequential if there are no overlapping transactions in $H$, i.e., every two transactions are related by the real-time order.

Valid, legal and multi-versioned histories. Let $H$ be a history and $r_k(x,v)$ be a successful read operation (i.e. $v \neq A$) in $H$. Then $r_k(x,v)$ is said to be valid if there is a transaction $T_j$ in $H$ that commits before $r_k$ and $w_j(x,v)$ is in evts($T_j$). Formally, $(r_k(x,v)$ is valid $\Rightarrow \exists T_j : (c_j \prec_H r_k(x,v)) \land (w_j(x,v) \in \text{evts}(T_j)) \land (v \neq A)$). We say that the commit operation $c_i$ is $r_k$'s valWrite and formally denote it as $H.valWrite(r_k)$. If there are multiple such committed transactions that write $v$ to $x$, then $r_k$ valWrite is the commit operation closest to $r_k$. The history $H$ is valid if all its successful read operations are valid.

We define $r_k(x,v)$’s lastWrite as the latest commit event $c_i$ such that $c_i$ precedes $r_k(x,v)$ in $H$ and $x \in \text{Wset}(T_i)$ ($T_i$ can also be $T_0$). Formally, we denote it as $H.lastWrite(r_k)$. A successful read operation $r_k(x,v)$ (i.e $v \neq A$), is said to be legal if transaction $T_i$ (which contains $r_k$’s lastWrite) also writes $v$ onto $x$. Formally, $(r_k(x,v)$ is legal $\Rightarrow (v \neq A) \land (H.lastWrite(r_k(x,v)) = c_i) \land (w_i(x,v) \in \text{evts}(T_i)))$. The history $H$ is legal if all its successful read operations are legal. Thus from the definitions we get that if $H$ is legal then it is also valid.

Figure 1 shows a pictorial representation of a history $H_1: r_1(x,0)\prec_H^RT w_2(x,1)\prec_H^RT w_2(x,10)\prec_H^RT c_1(y,0)\prec_H^RT c_0(y,1)\prec_H^RT c_1(y,0)$. It can be seen that in $H_1$, $c_0 = H.valWrite(r_2(x,0)) = H.lastWrite(r_1(x,0))$. Hence, $r_1(x,0)$ is legal. But $c_0 = H.valWrite(r_1(y,0)) \neq c_1 = H.lastWrite(r_1(y,0))$. Thus, $r_1(y,0)$ is valid but not legal.

We define a history $H$ as multi-versioned if it is valid but not legal. If a history $H$ is multi-versioned, then there is at least one read, say $r_i(x)$ in $H$ that is valid but not legal. The history $H_1$ is multi-versioned. Along the same lines, we say that a STM implementation is multi-versioned if it exports atleast one history that is multi-versioned.

Opacity. We say that two histories $H$ and $H'$ are equivalent if they have the same set of events. Now a history $H$ is said to be opaque [5] [6] if $H$ is valid and there exists a $t$-sequential legal history $S$ such that (1) $S$ is equivalent to $H$ and (2) $S$ respects $\prec_H^RT$, i.e $\prec_H^RT \subseteq \prec_S$. By requiring $S$ being equivalent to $H$, opacity treats all the incomplete transactions as aborted.

3. New Conflict Notion for Multi-Version Systems

3.1 Motivation for a New Conflict Notion

It is not clear if checking whether a history is opaque or can be performed in polynomial time. Checking for membership of multi-version view-serializability (MVSR) [14] chap. 3., the correctness criterion for databases, has been proved to be NP-Complete [11]. We believe that the membership of opacity, similar to MVSR, can not be efficiently verified.

In databases a sub-class of MVSR, conflict-serializability (CSR) [14] chap. 3. has been identified, whose membership can be efficiently verified. As a result, CSR is the commonly used correctness criterion in databases since it can be efficiently verified. In fact all known single-version schedulers known for databases are a sub-set of CSR. Similarly, using the notion of conflicts, a sub-class of opacity, conflict-opacity (co-opacity) can be designed whose membership can be verified in polynomial time. Further, using the verification mechanism, an efficient STM implementation can be designed that is permisive w.r.t co-opacity.

By storing multiple versions for each transaction object, multi-version STMs provide more concurrency than single-version STMs. But the main drawback of co-opacity is that it does not admit histories that are multi-versioned. In other words, the set of histories exported by any STM implementation that uses multi versions is not a subset of co-opacity. Thus it can be seen that the set co-opacity does not take advantage of the concurrency provided by using multiple versions. As a result, it is not clear if a multi-version STM implementation can be developed that is permisive w.r.t some subclass of opacity. In the rest of this sub-section, we formally define co-opacity and prove this result.

The following definitions and proofs are coming directly from [9]. We define co-opacity using conflict order [14] Chap. 3. as:

For two transactions $T_i$ and $T_m$ in $\text{txn}(H)$, we say that $T_k$ precedes $T_m$ in conflict order, denoted $T_k \prec_CO T_m$, if (w-r order) $\text{tryCk}(C) \prec_H \text{tryCm}(C)$ and $\text{Wset}(T_k) \cap \text{Wset}(T_m) \neq \emptyset$, (w-r order) $\text{tryCk}(C) \prec_H r_m(x,v), x \in \text{Wset}(T_k)$ and $v \neq A$, or (r-w order) $r_k(x,v) \prec_H \text{tryCm}(C), x \in \text{Wset}(T_m)$ and $v \neq A$.

Thus, it can be seen that the conflict order is defined only on operations that have successfully executed. Using conflict order, co-opacity is defined as follows:

DEFINITION 1. A history $H$ is said to be conflict opaque or co-opaque if $H$ is valid and there exists a $t$-sequential legal history $S$ such that (1) $S$ is equivalent to $H$ and (2) $S$ respects $\prec_H^RT$ and $\prec_CO$.

Readers familiar with the databases literature may notice co-opacity is analogous to the order commit conflict serializability (OCSR) [14].

LEMMA 1. Consider two histories $H_1$ and $H_2$ such that $H_1$ is equivalent to $H_2$ and $H_1$ respects conflict order of $H_2$, i.e., $\prec_H^RT \subseteq \prec_CO$. Then, $\prec_CO = \prec_H^RT$.

Proof. Here, we have that $\prec_CO \subseteq \prec_H^RT$. In order to prove $\prec_H^RT = \prec_CO$, we have to show that $\prec_CO \subseteq \prec_H^RT$. We prove this using contradiction. Consider two events $p,q$ belonging to transaction $T_1,T_2$ respectively in $H_2$ such that $(p,q) \in \prec_CO$ but $(p,q) \notin \prec_H^RT$. Since the events of $H_2$ and $H_1$ are same, these events are also in $H_1$. Thus, we have that either $(p,q) \in \prec_H^RT$ or $(p,q) \in \prec_CO$. But from our assumption, we get that the former is not possible. Hence, we get that $(p,q) \in \prec_CO \Rightarrow (p,q) \in \prec_H^RT$. But we already have that $(p,q) \in \prec_CO$. This is a contradiction.

LEMMA 2. Let $H_1$ and $H_2$ be equivalent histories such that $\prec_H^RT = \prec_CO$. Then $H_1$ is legal if $H_2$ is legal.

Proof. It is enough to prove the ‘if’ case, and the ‘only if’ case will follow from symmetry of the argument. Suppose that $H_1$ is legal. By contradiction, assume that $H_2$ is not legal, i.e., there is a read operation $r_j(x,v)$ (of transaction $T_j$) in $H_2$ with its lastWrite as $c_k$ (of transaction $T_k$) and $T_k$ writes $v \neq v$ to $x$, i.e. $w_k(x,u) \in \text{evts}(T_k)$. Let $r_j(x,v)$’s lastWrite in $H_1$ be $c_i$, Since $H_1$ is legal, $T_i$ writes $v$ to $x$, i.e. $w_i(x,v) \in \text{evts}(T_i)$.

Since $\text{evts}(H_1) = \text{evts}(H_2)$, we get that $c_i$ is also in $H_2$, and $c_k$ is also in $H_1$. As $\prec_H^RT = \prec_CO$, we get $c_i <_H^RT r_j(x,v) \land c_k <_H^RT r_j(x,v)$. Since $c_i$ is the lastWrite of $r_j(x,v)$ in $H_1$ we derive that $c_k <_H^RT c_i$ and thus, $c_k <_H^RT c_i <_H^RT r_j(x,v)$. But this contradicts the assumption that $c_i$ is the lastWrite of $r_j(x,v)$ in $H_2$. Hence, $H_2$ is legal.

We now prove that if a history is multi-versioned, then it is not in co-opacity.

LEMMA 3. If a history $H$ is multi-versioned then $H$ is not in co-opacity. Formally, $\langle (H \text{is multi-versioned}) \Rightarrow (H \notin \text{co-opacity}) \rangle$.

Proof. We prove this using contradiction. Assume that $H$ is multi-versioned, i.e. $H$ is valid but not legal. But suppose that $H$ is in
co-opacity. From the definition of co-opacity, we get that there exists a sequential and legal history $S$ such that $\prec^c_H \subseteq \prec^c_S$. From Lemma 4, we get that $\prec^c_H = \prec^c_S$. Combining this with Lemma 5 and the assumption that $H$ is not legal, we get that $S$ is not legal. But this contradicts out assumption that $S$ legal. Hence, $H$ is not in co-opacity.

Having shown the shortcoming of conflicts, we now define a new conflict notion in the next sub-section that will accommodate multi-versioned histories as well.

### 3.2 Multi-Version Conflict Definition

We define a few notations to describe the conflict notion. Consider a history $H$. For a read $r_i(x, v)$ in $H$, we define $r_i$’s valWrite, formally $H$.valWrite($r_i$), as the commit operation $c_i$ belonging to the transaction $T_i$ that occurs before $r_i$ in $H$ and writes $v$ to $x$. If there are multiple such committed transactions that write $v$ to $x$ then the valWrite is the commit operation closest to $r_i$.

**Definition 2.** For a history $H$, we define multi-version conflict order, denoted as $\prec^{mvc}_H$ between operations of $H$ as follows: (a) commit-commit ($c$-$c$) order: $c_i \prec^{mvc}_H c_j$ if $c_i \prec_H c_j$ for two committed transaction $T_i, T_j$, and both of them write to $x$. (b) commit-read ($c$-$r$) order: Let $r_i(x, v)$ be a read operation in $H$ with its valWrite $c_j$ (belonging to the committed transaction $T_j$). Then for any committed transaction $T_k$ that writes to $x$ and either commits before $T_j$ or is same as $T_j$, formally $(c_k \prec_H c_j) \lor (c_k = c_j)$, we define $c_k \prec^{mvc}_H r_i$. (c) read-commit ($r$-$c$) order: Let $r_i(x, v)$ be a read operation in $H$ with its lastWrite as $c_j$ (belonging to the committed transaction $T_j$). Then for any committed transaction $T_k$ that writes to $x$ and commits after $T_j$, i.e. $c_j \prec_H c_k$, we define $r_i \prec^{mvc}_H c_k$.

Observe that the multi-version conflict order is defined on the operations of $H$ and not $H$. The set of conflicts in $H$ are: $[c$-$c : (c_0, r_1(x, 0)), (c_0, r_1(y, 0))], [r$-$c : (r_1(x, 0), c_2), (r_1(y, 0), c_1)], [c$-$c : (c_0, c_2)]$.

We say that a history $H'$ satisfies the multi-version conflict order of a history $H$, $\prec^{mvc}_H$ if: (1) the events of $H'$ are same as $H$, i.e. $H'$ is equivalent to $H$. (2) For any two operations $o_p$ and $o_p$, $o_p \prec^{mvc}_H o_p$ implies $o_p \prec_H o_p$. We denote this by $H' \prec^{mvc}_H$. Otherwise, we say that $H'$ does not satisfy $\prec^{mvc}_H$ and denote it as $H' \not\prec^{mvc}_H$.

Note that for any history $H$ that is multi-versioned, $H'$ does not satisfy its own multi-version conflict order $\prec^{mvc}_H$. For instance the multi-versioned order in history $H'$ consists of the pair: $(r_1(y, 0), c_2)$. But $c_2$ occurs before $r_1(y, 0)$ in $H$.1 We formally prove this property using the following lemmas.

**Lemma 4.** Consider a (possibly multi-versioned) valid history $H$. Let $H'$ be a history which satisfies $\prec^{mvc}_H$. Then $H'$ is valid and $\prec^{mvc}_H = \prec^{mvc}_H$. Formally, $(H$ is valid) $\land (H' \prec^{mvc}_H) \implies (H'$ is valid) $\land (\prec^{mvc}_H = \prec^{mvc}_H)$.

**Proof.** Here, we have that $H$ is valid and $H'$ satisfies $\prec^{mvc}_H$. Thus all the events of $H$ and $H'$ are the same. The definition of satisfaction says that the events of $H'$ are ordered according to multi-version conflict order of $H$. Thus, it can be verified that all the multi-version conflict orders of both histories are the same, i.e. $\prec^{mvc}_H = \prec^{mvc}_H$. Since $H$ is valid and $H'$ has the same c-r multi-version conflict order as $H$, the valWrite of all the read operations in $H'$ occur before the corresponding reads in $H'$. Hence $H'$ is valid as well.

**Lemma 5.** Consider a (possibly multi-versioned) valid history $H$. Let $H'$ be a valid history (which could be same as $H$). If $H'$ satisfies $\prec^{mvc}_H$ then $H'$ is legal. Formally, $(\langle H'$ is valid $\rangle \land (H' \prec^{mvc}_H)) \implies (H'$ is legal).

**Proof.** Assume that $H'$ is not legal. Hence there exists a read operation, say $r_i(x, v)$, in evts($H'$) that is not legal. This implies that lastWrite of $r_i$ is not the same as its valWrite. Let $c_l = H'.lastWrite(r_i) \neq H'.valWrite(r_i) = c_o$. Let $w_i(x, u) \in evts(T_i)$ and $w_v(x, v) \in evts(T_v)$. Since $H'$ is valid and $c_l$ is the lastWrite of $r_i$, we get the following order of the events:

$$c_o \prec_H c_l \prec_H r_i \quad (1)$$

Since $H' \prec^{mvc}_H$ and $H$ is valid, from Lemma 4 we get that $\prec^{mvc}_H = \prec^{mvc}_H$. Hence, $H'$ must satisfy its own multi-version conflict order, $\prec^{mvc}_H$. Now combining Eqn (1) with the definition of r-w multi-version conflict order, we get that $r_i \prec^{mvc}_H (\ handicraft{c_l}$. But since $H' \prec^{mvc}_H$, we get that $r_i \not\prec^{mvc}_H c_l$. But this contradicts Eqn (1). Hence, $r_i$ must be legal which in turn implies that $H'$ must be legal.

Using this lemma, we get the following corollary.

**Corollary 6.** Consider a (possibly multi-versioned) valid history $H$. Let $H'$ be a multi-versioned history (which could be same as $H$). Then, $H'$ does not satisfy $\prec^{mvc}_H$. Formally, $(\langle H'$ is multi-versioned $\rangle \implies (H' \not\prec^{mvc}_H))$.

**Proof.** We are given that $H'$ is multi-versioned. This implies that $H'$ is not legal. From the contrapositive of Lemma 5 we get that $H' \not\prec^{mvc}_H$.

### 4. Multi-Version Conflict Opacity

We now illustrate the usefulness of the conflict notion by defining another subset of opacity mvc-opacity which is larger than co-opacity. We formally define it as follows (along the same lines as co-opacity):

**Definition 3.** A history $H$ is said to be multi-version conflict opaque or mvc-opaque if $H$ is valid and there exists a t-sequential history $S$ such that (1) $S$ is equivalent to $H$ and (2) $S$ respects $\prec^{mvc}_S$ and $S$ satisfies $\prec^{mvc}_H$. In order to prove that $H$ is opaque, it is sufficient to show that $S$ is legal. Since $S$ satisfies $\prec^{mvc}_H$, from Lemma 5 we get that $S$ is legal. Hence, $H$ is opaque as well.

Thus, this lemma shows that mvc-opacity is a subset of opacity. Actually, mvc-opacity is a strict subset of opacity. Consider the history $H2 = r_1(x, 0)r_2(z, 0)r_3(z, 0)w_1(x, 5)c_1r_4(z, 5)w_2(x, 10)w_1(y, 15)c_2r_3(x, 5)w_3(y, 25)c_3$. The set of multi-version conflicts in $H2$ are (ignoring the conflicts with $c_3$): $[c$-$c : (c_1, r_2(x, 5)), (c_1, r_4(z, 5))], [r$-$c : (r_3(x, 5), c_2), [c$-$c : (c_1, c_2), (c_1, c_3), (c_2, c_3)]$. It can be verified that $H2$ is opaque with the equivalent t-sequential history being $T_1T_2T_3$. But there is no multi-version conflict equivalent t-sequential history. This is because of the conflicts: $(r_3(x, 5), c_2), (c_2, c_3)$. Hence, $H2$ is not mvc-opaque.
Next, we will relate the classes co-opacity and mvc-opacity. In the following lemma, we show that co-opacity is a subset of mvc-opacity.

**Theorem 8.** If a history $H$ is co-opaque, then it is also mvc-opaque.

**Proof.** Since $H$ is co-opaque, we get that there exists an equivalent legal t-sequential history $S$ that respects the real-time and conflict orders of $H$. Thus if we show that $S$ satisfies multi-version conflict order of $H$, it then implies that $H$ is also mvc-opaque. Since $S$ is legal, it turns out that the conflicts and multi-version conflicts are the same. To show this, let us analyse each conflict order:

- **c-c order:** If two operations are in c-c conflict, then by definition they are also ordered by the c-c multi-version conflict.
- **c-r order:** Consider the two operations, say $c_j$ and $r_i$ that are in conflict (due to a transaction object $x$). Hence, we have that $c_k <_H r_i$. Let $c_j = H.valWrite(r_i)$. Since, $S$ is legal, either $c_k = c_j$ or $c_k <_H c_j$. In either case, we get that $c_k \prec_{mv} r_i$.
- **r-c order:** Consider the two operations, say $c_j$ and $r_i$ that are in conflict (due to a transaction object $x$). Hence, we have that $r_i <_H c_k$. Let $c_j = H.valWrite(r_i)$. Since, $S$ is legal, $c_j <_H r_i <_H c_k$. Thus in this case also we get that $r_i \prec_{mv} c_k$.

Thus in all the three cases, conflict among the operations in $S$ also results in multi-version conflict among these operations. Hence, $S$ satisfies the multi-version conflict order. □

This lemma shows that co-opacity is a subset of mvc-opacity. The history $H_1$ is mvc-opaque but not in co-opaque. Hence, co-opacity is a strict subset of mvc-opacity. Figure 2 shows the relation between the various classes.

**Figure 2.** Relation between the various classes

### 4.1 Graph Characterization of MVC-Opacity

In this section, we will describe graph characterization of mvc-opacity. This characterization will enable us to verify its membership in polynomial time.

Given a history $H$, we construct a multi-version conflict graph, $MVCG(H) = (V, E)$ as follows: (1) $V = txns(H)$, the set of transactions in $H$ (2) an edge $(T_i, T_j)$ is added to $E$ whenever

1. real-time edges: If $T_i$ precedes $T_j$ in $H$
2. mvc edges: If $T_i$ contains an operation $p_i$ and $T_j$ contains $p_j$ such that $p_i \prec_{mv} p_j$.

Based on the multi-version conflict graph construction, we have the following graph characterization for mvc-opacity.

**Theorem 9.** A valid history $H$ is mvc-opaque iff $MVCG(H)$ is acyclic.

Figure 3 shows the multi-version conflict graphs for the histories $H_1$ and $H_2$.

**Figure 3.** multi-version conflict graphs of $H_1$ and $H_2

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