Oze: Decentralized Graph-based Concurrency Control for Real-world Long Transactions on BoM Benchmark

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ABSTRACT
In this paper, we propose Oze, a new concurrency control protocol that handles heterogeneous workloads which include long-running update transactions. Oze explores a large scheduling space using a fully precise multi-version serialization graph to reduce false positives. Oze manages the graph in a decentralized manner to exploit many cores in modern servers. We also propose a new OLTP benchmark, BoMB (Bill of Materials Benchmark), based on a use case in an actual manufacturing company. BoMB consists of one long-running update transaction and five short transactions that conflict with each other. Experiments using BoMB show that Oze keeps the abort rate of the long-running update transaction at zero while reaching up to 1.7 Mtpm for short transactions with near-linear scalability, whereas state-of-the-art protocols cannot commit the long transaction or experience performance degradation in short transaction throughput.

CCS CONCEPTS
• Information systems → Database transaction processing.

KEYWORDS
concurrency control, OLTP benchmark, long-running transaction

1 INTRODUCTION
Transaction processing has been used for applications and workloads in various industries. Concurrency control is the core of transaction processing. Various concurrency control protocols have been proposed to take advantage of the recent architectural evolution such as many-core and large memory capacity [25, 37–39, 43], which have achieved high performance and scalability.

Existing concurrency control protocols do not assume a certain type of heterogeneous workload in which a long-running update transaction and multiple types of short transactions are mixed. Such heterogeneous workloads exist, for example, in OLTP systems for manufacturing industries. The system there runs a transaction that builds up a tree structure based on an item master and an item component master, referred to as a Bill of Materials, or BoM, and calculates product costs and requirements [11]. This transaction (referred to as the L1 transaction; see Section 2 for details) is a long-running update transaction because it must read a large number of records and write the results. In addition to L1, the system runs a short transaction (called the S1 transaction) that updates the raw material cost referred to in the calculation of the product cost, and a short transaction (called the S2 transaction) that uses the product cost in other applications. Handling these concurrent transactions that interfere with each other remains challenging.

Because existing concurrency control protocols are not designed for such heterogeneous workloads, it is common for companies to process long transactions at night when online short transactions do not occur [4]. However, this workaround is sometimes infeasible. The freshness and accuracy of the product costs, which are kept by the long transactions, are essential since the product costs are used as input for optimal production planning in manufacturing resource planning (MRP) [40], especially budgeting and demand planning. Generally, an accuracy of 98% in BoM composition and 95% in inventory is required to obtain accurate results in MRP because input errors accumulate from pile-up calculations [11, 33]. Meanwhile, the cost of raw materials and the components of items, which are the basis of product costing, can frequently change due to supply chain disruptions caused by disasters and infectious diseases1. Therefore, there is a need for on-demand product costing not at night but during the day when online short transactions occur [8, 17].

1Supply chain disruptions and price fluctuations have occurred due to the extensive damage caused by the Great East Japan Earthquake and the resulting nuclear power plant accident, as well as lockdowns to prevent the spread of COVID-19 [1, 27, 28].
What happens if modern concurrency control protocols try to handle such heterogeneous workloads? The abort rate of the L1 transaction is shown in Figure 1 when the L1, S1, and S2 transactions run concurrently using state-of-the-art protocols. The horizontal axis is the number of products to be costed in one transaction, which corresponds to the length of the L1 transaction. As shown in the figure, none of the existing protocols can commit the long transaction, or if they can, the success rate is less than one percent. OCC protocols such as Silo [37] and TicToc [43] abort the L1 transaction because the S1 transaction updates the cost of raw materials before L1 is completed. MOCC [39], which combines OCC and the advantages of a lock-based scheme, rarely avoids aborts even with pessimistic behavior. ERMIA [38] and Cicada [25] cannot commit any L1 transactions because they are interfering with concurrent S2 transactions. The details are described in Section 2.5.

Existing lock-based [18] and deterministic [15, 36] approaches can handle this workload under a certain condition where BoMs do not change before and after the L1 transaction, as shown in Figure 8. We call such a fixed BoM a static BoM. Even though these approaches can commit the L1, they suffer from performance degradation of the S1 that must wait for the L1. More importantly, our target BoMs must often be updated by another transaction which changes the composition of a product to dynamically respond supply chain disruption. We call such a BoM a dynamic BoM. Deterministic approaches cannot commit the L1 anymore when handling a dynamic BoM. Even if they use reconnaissance queries [36] to know BoM trees in advance, they cannot guarantee the trees are not changed without additional application-level assistance, e.g., stop transactions that modify BoMs. Such an application-level workaround is not the direction of our goal.

In this paper, we first propose Oze, a concurrency control protocol that can handle heterogeneous workloads which include long and short transactions. Oze generates serializable schedules using a multi-version serialization graph (MVSG) [3]. MVSGT [20] and MVSGA [19] are conventional graph-based approaches that generate serializable schedules in large scheduling spaces: multi-version conflict serializability (MCSR) and multi-version view serializability (MVS). However, their protocols are rather theoretical and there are no available implementations, to the best of our knowledge. In addition, they assume centralized graph management, which cannot benefit from many cores and achieve high scalability. We present a decentralized implementation of Oze that can take advantage of many-core environments by using a logically single graph on each record.

Second, we present a new benchmark, BoMB (Bill of Materials Benchmark), which reproduces the heterogeneous workload described above. TPC-C [12] and TPC-E [13] are widely used as de facto standard benchmarks for OLTP systems; however, neither includes long-running update transactions. In contrast, BoMB’s target application is a cost management system for manufacturing, which consists of six transactions: calculating product costs (L1), updating raw material costs that are used by L1 (S1), posting journal vouchers based on the calculated product cost (S2), changing a product (S3), changing a raw material of a product (S4), changing a product quantity (S5). The transactions of BoMB are designed and implemented on CCBench [34], which is a benchmarking platform for concurrency control protocols for in-memory database systems, to allow fair comparison and evaluation between various protocols.

Third, we evaluate Oze with modern concurrency control protocols using BoMB. Experimental results show that Oze keeps the abort rate of the long-running update transactions at zero while reaching up to 1.7 Mtpm for short transactions with near-linear scalability, whereas state-of-the-art protocols cannot commit the long transaction or experience performance degradation in the throughput of short transactions.

The rest of this paper is organized as follows. First, in Section 2, we define the workload and its database in BoMB. Next, we describe the design of the Oze protocol in Section 3 and the implementation of Oze for multi-core systems in Section 4. In Section 5, we evaluate several protocols using BoMB. In Section 6, we describe related work. Finally, we conclude this paper in Section 7.

2 BOM BENCHMARK

This section describes an overview, database schema, and workload of BoM Benchmark (BoMB). We also show how and why existing protocols cannot effectively handle the BoMB workload.

2.1 Background and Overview

We use a food manufacturing company that produces bread nationwide as our reference when designing the BoMB workload. In the target food manufacturing industry, the supply chain can be disrupted by various reasons such as climate change, and the prices of raw materials often change as well. Therefore, it is necessary to accurately gauge manufacturing costs and schedule an optimal production plan and supply chain. In order to reflect such needs, the BoMB workload is configured assuming a system capable of on-demand inventory control, cost control, and production planning. Figure 2 shows an overview of the target system and workload. We assume that the system consists of an MRP system that manages products and resources needed for manufacturing and a perpetual inventory management system that continuously manages the inventory. The MRP consists of cost management, budgeting, demand
planning, and supply chain management (SCM) modules, and each module accesses one database. The cost management generates the most complicated workload among these modules due to the long-running update transactions. Thus, for BoMB, we focus on emulating the workload of the cost management module.

The BoMB workload has six transactions that are directly related to product costing and its input/output: L1 and S1–S5 transactions. L and S stand for “long” and “short,” respectively. All of these transactions generally occur in manufacturing industries [29, 41] and can be widely applied other than in bakeries.

### 2.2 Tables and Parameters

BoMB uses seven tables shown below. The underlined attribute is the primary key. Note that INT16, INT32, and INT64 are integers of 16, 32, and 64 bits, respectively. Adjustable parameters for the BoMB are shown in Table 1. The default values are set on the basis of the actual values of the referenced bread manufacturer; these would change depending on the industry.

#### Table 1: BoMB parameters.

| Parameters               | Default | Description                           |
|--------------------------|---------|---------------------------------------|
| factories                | 8       | Number of factories                   |
| product-types            | 72,000  | Number of product types               |
| material-types           | 198,000 | Number of material types              |
| raw-material-types       | 75,000  | Number of raw material types          |
| material-trees-per-product | 5      | Number of material trees per product  |
| material-tree-size       | 10      | Number of materials in a material tree|
| raw-materials-per-leaf   | 3       | Number of raw materials in a leaf material |
| target-products          | 100     | Number of products manufactured in a factory |
| target-materials         | 1       | Number of raw materials for update    |

#### Figure 3: Example of BoM tree.

quantity in each record and hierarchically represents BoM trees. Details of the structure of BoM trees and product costing using this table are described in Section 2.3.

- **material-cost**(*factory_id* INT32, *item_id* INT32, *stock_quantity* DOUBLE, *stock_amount* DOUBLE): The material-cost table manages the cost of raw materials, the stock quantity, and the amount of the raw materials for each factory and item.
- **result-cost**(*factory_id* INT32, *item_id* INT32, *cost* DOUBLE): The result-cost table contains the latest cost calculation results for each product in each factory.
- **journal-voucher**(*voucher_id* INT64, *date* DATE, *debit* INT32, *credit* INT32, *amount* DOUBLE, *description* VARCHAR): Because the cost calculation result is used for each module, e.g., budgeting, demand planning, and SCM, it is created as a journal voucher as needed and stored in this table.

### 2.3 BoM Tree

The bom table is a list of intermediate and raw materials and the quantities required to make a particular product and their quantities. It can be logically expressed in a tree structure. An example of a BoM tree is shown in Figure 3. The product consists of several major materials (hereafter, “root materials” for convenience). For example, in the production of sandwiches, the major materials correspond to bread and the ingredients inside (e.g., tuna salad). Each root material is made from multiple materials. In the example of bread, the material is dough, and the raw materials are flour, yeast, etc.

To support BoMs in other manufacturing industries [29, 41] such as in aircraft and robots industries, we introduce parameters for BoM trees: the number of root materials, the number of materials that make up each root material tree (material-tree-size), and the number of raw materials in each leaf material (raw-materials-per-leaf).

When starting the benchmark, the BoM trees are initialized as follows. (1) Select a set of materials with size material-tree-size. (2) Select the root material from them. (3) Add the remaining materials as child nodes to random tree nodes. (4) Add raw-materials-per-leaf raw materials to each leaf of the tree. Raw materials are randomly selected from raw-materials-types. (5) After generating all trees until materials-types materials are exhausted, assign material-trees-per-product trees to each product. Though the
tree structure is randomly configured by default for versatility in BoMB, skew may be given depending on the target industry.

The product cost is calculated using the BoM tree as follows. (1) Determine the products to be costed. (2) Refer to the bom table, recursively acquire the materials that comprise the product, and construct a BoM tree. Each tree node holds the item ID, the list of child item IDs, the unit price, and the required quantity. (3) Obtain the stock_quantity and stock_amount for each raw material which is a leaf node of the BoM tree, and set the unit cost calculated from them. (4) Recursively call the calculate_cost() function shown in Algorithm 1 from the root node of the BoM tree.

### 2.4 Transactions

**L1 (update-product-cost):** The L1 transaction is a long transaction that builds the BoM tree described in Section 2.3 and calculates the product cost. First, it selects one factory at random and obtains item_id of all products manufactured at the factory and their quantity referring to the product table. Then, it builds a BoM tree for a product, calculates the cost, and writes the result to cost of the result-cost table. It repeats these steps for all products; the number of products (target-products) means how many products are currently manufactured at each factory. This parameter determines the length of the long transaction. When the L1 transaction is executed with the default values in Table 1, there are a total of about 20,000 read/scan records and 100 write records.

**S1 (update-material-cost):** The S1 transaction is a short transaction that changes the cost of raw materials. First, it selects a factory and a raw material uniformly at random and uses them as keys to read records from the material-cost table. Then, it adds or subtracts an arbitrary value to/from the current stock_quantity of the record and writes on the record. Depending on the applications, updates may occur all at once across multiple factories and raw materials, so the number of raw materials to be updated (target-materials) is allowed to be configured. By default, S1 transactions perform one single read-modify-write on a record.

**S2 (issue-journal-voucher):** The S2 transaction is a short transaction that creates a journal voucher based on the calculated product cost. It selects a factory uniformly at random and scans the result-cost table to obtain the cost of each product in the factory. Then it calculates the amount from the cost and production volume (given as an input) for each product. Finally, it inserts the journal vouchers (new records) into the journal-voucher table with the debit as the product and the credit as the work in process. The number of records inserted is determined by target-products.

**S3 (change-product):** The S3 transaction is a short transaction that replaces an old product with a newly-developed product. It selects a product from a factory uniformly at random and deletes the product. Then it decides a unique item ID for a new product and chooses root materials randomly according to the number of material-trees-per-product. Item IDs can be cached; they can be retrieved in advance and excluded from transactions’ read set. Finally, new records with the chosen item ID are inserted into the bom table.

**S4 (change-raw-material):** The S4 transaction is a short transaction that replaces a raw material of a product with a different one due to changes in purchasing conditions (e.g., change a flour X to X'). It selects a record that consists of a material and a raw material from the bom table and a raw material from the item table uniformly at random. Then it deletes the old record and inserts a new record with the chosen raw material. bom records and item IDs can be cached the same as the above transaction.

**S5 (change-product quantity):** The S5 transaction is a short transaction that updates a manufacturing quantity of a product in a factory as a result of demand planning. It selects a factory and a product uniformly at random and then updates the record in the product table with a given value of quantity.

**Regulation for Execution.** BoMB can be run with two settings according to the target BoM characteristics: static and dynamic BoM. For static BoM, BoMB runs L1, S1, and S2 transactions. For dynamic BoM, it additionally runs S3, S4, and S5 transactions that modify the product and bom table. Note that BoMB requires at least one thread for each transaction to keep issuing requests so that all (three or six) types of transactions are executed concurrently as a mixed workload. To generate the workload, it may be desirable to control the request ratio of each transaction as predefined in TPC-C. However, if no long transaction can be committed, all threads will run long transactions while continuing to retry, or short transactions will be stalled to maintain the specified ratio. In that case, complicated dependencies between the long and short transactions no longer occur. Since this is not the workload we would like to model, we prepare at least one thread in charge of generating each type of transaction to ensure interferences occur.

**Measurements.** What we want to measure using BoMB is how likely long-running update transactions can be committed and how many online short transactions can be committed concurrently. Therefore, in BoMB, we use each type of transaction’s throughput and abort rate as the measurement items.

### 2.5 BoMB with State-of-the-art Concurrency Control Protocols

OCC protocols such as Silo [37] and TicToc [43] struggle to handle the BoMB workload. They verify that the read records are not updated to confirm whether a transaction can be committed (i.e., read validation). Since an S1 transaction updates the raw material cost with a high probability before the L1 transaction commits, the L1 repeatedly aborts in the validation phase. Figure 4(a) shows the rate of records that have already been updated (i.e., invalid records) in the read set of L1 at the validation phase. The x-axis is

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In the original protocol, the transaction will be aborted when an updated record is found, but we check the entire read set to calculate the invalid record rate.
the number of products handled by the L1 transaction; operations scale with this number. It is difficult to commit the L1 because the number of invalid records increases as the number of products increases. MOCC combines OCC with a pessimistic scheme using locks and a hotspot counter. However, since not all records are treated pessimistically, invalid records still remain.

Timestamp adjustments used in some OCC variants [5, 23, 24] do not contribute to the L1 completion with or without priority setting. This is because although an S1 can update records while protecting those already read by an L1, the L1 scheduled in the order L1 < S1 will have no room for timestamp adjustments once another S1 update a record the L1 is about to read.

MVCC, which is used by ERMIA [38] and Cicada [25], holds multiple versions of records so that a reader can use older versions even if the record is updated by concurrent writers. MVCC performs with high throughput because the read is not hindered even in highly-contended workloads, which single-version OCC struggles to handle. MVCC uses two timestamps: the write timestamp, which indicates when the version became valid, and the read timestamp which indicates how long the version is valid. Both ERMIA and Cicada update the read timestamp (known as the high watermark in ERMA) of a record when an S2 transaction, which reads the record in the result-cost table, is committed. Meanwhile, when an L1 transaction tries to update the same record after the S2 transaction updates the read timestamp of a version of the record, the L1 aborts as a false positive.

Figure 4(b)(c) show the extent to which the L1 transaction is actually late. The x-axis is the same as Figure 4(a), and the y-axis on the left side is the delay rate which is the rate of the delayed time to commit to the transaction execution time. Let $t_b$, $t_r$, and $t_e$ be the begin timestamp, the observed minimum read timestamp that caused the abort, and the end timestamp. Then, the delay rate is calculated by $(t_e - t_r)/(t_e - t_b)$ and must be zero to commit the transaction. The y-axis on the right side is the abort rate. Both protocols are not in time at all because the S2 updates the read timestamp at a relatively early phase as the duration of the L1 becomes longer.

3 OZE DESIGN

The basic idea of Oze is to allow fully-precise ordering of transactions with a 3-phase protocol using a multi-version serialization graph. In this section, we describe these designs and the correctness of the protocol. A decentralized implementation of Oze that exploits modern many-core architecture is presented in Section 4.4.

3.1 Graph-based Precise Ordering

Timestamp-based optimistic protocols such as OCC and MVCC provide efficiency, but they sacrifice scheduling space obtained by managing the precise order with a serialization graph as a trade-off. Even though MVCC is known to have a large scheduling space, the existing protocols [25, 38] cannot commit long transactions in BoMB, as shown in Figure 1 and 4. The S2 transaction has a dependency on the record read by the L1 transaction but no dependency on the write record. Nevertheless, the existing protocols have to abort L1 with a false positive because they simplify the dependency using the size of the timestamp. In contrast, Oze tracks such dependencies without omission by using MVSG [3] and handles all transactions of BoMB concurrently in a large scheduling space.

MVSG is a directed acyclic graph that has edges for the reads from relationships between transactions and for the version orders. That is, when there is a transaction $T_i$ that reads $x$ written by transaction $T_j$ ($w_j(x_j) \rightarrow r_j(x_j)$), an edge is added from $T_j$ to $T_i$. In addition, if there is another transaction $T_k$ that writes $x$ and the version order is $x_j \ll x_k$, then an anti-dependency edge is added from $T_i$ to $T_k$ so that $T_i$ will read the latest version in the equivalent monoversion schedule; i.e., it does not break the view of $T_i$. If the version order is $x_k \ll x_j$, then the edge is added from $T_k$ to $T_j$.

Finding all possible version orders that make a multi-version serializable schedule is an NP-complete problem [3, 30]. Oze simplifies the problem by ordering a transaction before or after the version read by the concurrent transactions and accepting false positives to obtain a solution in such a vast search space efficiently. Oze first tries postponing the version so that the newer version in chronological order becomes the newer version in the serialization order. Here, postponing of $T_k$ means to select the order of $x_j \ll x_k$ when $w_j(x_j)$ and $r_j(x_j)$ are preceding as in the previous example. If postponing breaks serializability (i.e., a cycle occurs in MVSG), then Oze uses a technique order forwarding, which tries preposing $(x_k \ll x_j)$ to expand scheduling space.

With order forwarding, Oze changes the version order while avoiding breaking the concurrent transactions’ view, i.e., as long as the forwarding transaction does not interrupt the writer of the version and its readers. Order forwarding enables Oze to schedule transactions in the MVSR space, which is larger than the space generated by the MVSGT protocol [20].

3.2 3-Phase Order Construction Protocol

We design an optimistic multi-version protocol suitable for in-memory DBMS to reduce the interference of both memory access
and lock on records among concurrent transactions. Figure 5 shows an overview of Oze that consists of the following three phases.

Local Ordering: Oze executes a transaction while reading committed versions and writing new ones in the thread-local area. When reading, the transaction selects the latest committed version from the version list sorted by the serialization order, and the read-from edge is added to the graph. If the graph is still acyclic (i.e., serializable), the transaction proceeds to the next step. If the graph has a cycle, then it selects and checks an older version until it finds a version without making a cycle. The transaction adds anti-dependency edges from itself to the writers of newer versions than the selected one. When writing, the transaction only puts the new version of the record in the local write set to reduce unnecessary interferences on the records and the graph. Only the reads-from relationship is reflected on the graph in the local ordering phase. At this point, the order is partially and tentatively determined; selecting version orders is deferred to the global ordering phase.

Global Ordering: In the global ordering phase of Oze, a transaction determines version orders that can guarantee serializability. This phase is performed after accepting a commit request or finishing the execution of transaction logic. The transaction selects a version order for each record in the write set and adds a corresponding edge. As mentioned in Section 3.1, the transaction first tries the postponing version order, and if it makes a cycle, it tries preposing by order forwarding. After confirming there is no cycle, it adds a pending version (that cannot be read at this point) to the record while maintaining the serialization order. If the version orders can be determined while keeping the graph acyclic for all write records, the transaction proceeds to the finalizing phase for committing.

Finalizing: For a transaction that passed the global ordering phase without aborting, Oze changes the status of versions written by the transaction to committed.

3.3 Example

The following example describes the behavior of the Oze protocol. Consider schedule $s$, which consists of read, write, and commit operations from the transaction $T_1$ to $T_4$. The notation corresponds to the multi-version full schedule in the literature [20].

$$s = w_1(x_1)w_2(y_2)c_1c_2r_3(x_1)r_4(y_2)w_3(y_3)c_3w_4(x_4)c_4$$

First, after committing $T_1$ and $T_2$, $T_3$ and $T_4$ read $x_1$ and $y_2$, respectively, as indicated by the blue arrows in Figure 6. The edges for reads-from (dependency edges) are added. Next, $T_3$ verifies whether $y_2 < y_3$ (postposing) can be chosen in the version order of $y$ when committing after writing $y_1$. Specifically, as shown by the solid red arrow in the figure, the Oze protocol adds the anti-dependency edge from $T_4$ to $T_3$ and checks if there is a cycle. In this example, there is no cycle and $T_3$ is committed.

In contrast, when committing after writing $x_4$, $T_4$ creates a cycle if it tries to add a postponing edge from $T_3$ to $T_4$ (i.e., the version order $x_1 < x_3$) due to $T_3$’s read of $x_1$. Thus, it will put a preposing edge from $T_4$ to $T_1$ to try another version order $x_3 < x_1$ as shown by the dashed red arrow in the figure. This order forwarding keeps the graph acyclic, so $T_4$ can also be committed. The final serialization order is $T_2 < T_4 < T_1 < T_3$, which is different from the chronological order. Note that Oze can still ensure linearizability [21] by introducing an epoch and restricting the forwarding within the epoch, as detailed in Section 4.

3.4 Correctness

Theorem 3.1. If the Oze scheduler works correctly, i.e., if it outputs schedule $s$ and computes version order $\prec$, then $(s, \prec)$ is multi-version view serializable.

Proof. Let $G(s)$ be the multi-version serialization graph produced by the scheduler after having output $s$. $G(s)$ is acyclic, so let $s'$ be any partial schedule of the transactions in $s$ in which the serialization order of the transactions is compatible with the edges of $G(s)$. Let $r_i(x_j)$ be any reads-from relation in $(s, \prec)$. Then $j \rightarrow i$ is an edge in $G(s)$, so $T_j$ comes before $T_i$ in $s'$. For any other transaction $T_k$ which writes $x$, there must be either $k \rightarrow j$ or $i \rightarrow k$ as an edge of $G(s)$ since the scheduler decides a version order based on...
4 OZE IMPLEMENTATION

We describe a centralized implementation of Oze with a single MVSG, followed by a decentralized one in Section 4.4 and 4.5.

4.1 Data Structure

Transaction: Each transaction worker thread has a transaction ID (txid) that is assigned at the beginning and a read/write set. The transaction ID consists of an epoch, worker thread ID, and local counter. We introduce the epoch to ensure linearizability and facilitate garbage collection. Like Silo, a dedicated thread increments the global epoch at regular intervals, and each worker thread refers to it. The read set stores the read version pointer with keys, and the write set stores the written versions with keys.

Record: The structure of the database record is shown in Figure 7. The record has a linked list of versions with transactions’ serialization order; specifically, it has a pointer (record.latest) to the last version of the list. Each version has txid of the version creator, the pointer to the previous version, and the state. In addition, the decentralized implementation described in Section 4.4 holds a pointer to the multi-version serialization graph (MVSG, or simply ‘graph’) managed on a per-record basis.

Graph: The structure of the graph in Oze is shown in Figure 7. The graph is represented as a map whose key is txid and whose value is the node of the graph (txnode). Each node has three lists of txids and the transaction’s read set. The first is read_follower, a list of transactions that read the version written by the transaction, which corresponds to the reads-from edges in the follower’s perspective. The second is write_follower, a list of transactions that write a version newer than the version written by the transaction, which corresponds to the version order edges. The third is from, a list of transactions that have any edges pointed from the transaction. Note that Figure 7 holds a graph for each record as the decentralized implementation, but a centralized implementation shares a single graph using the same structure.

Algorithm 2: Local ordering phase (read and write)

```
1 Function readtxn, record
2   ver = record.latest
3   while ver do
4     graph[ver.txid].read_follower.add(txn.txid)
5     if is_acyclic(graph) then
6       break
7     graph[ver.txid].read_follower.remove(txn.txid)
8     graph[txn.txid].write_follower.add(ver.txid)
9     ver = ver.next
10    if ver then
11       txn.read_set.add((record, ver))
12       graph[txn.txid].read_set.add(record, ver)
13   else
14     abort()
15 Function writtxn, record
16   ver = create_version(txn.txid)
17   txn.write_set.add((record, ver))
```

4.2 Read and Write in Local Ordering Phase

As described in Section 3.2, Oze executes the local ordering phase, global ordering phase, and finalizing phase in that order. We describe the read and write protocol in the local ordering phase below.

Lines 1–14 of Algorithm 2 show Oze’s read protocol. The read protocol is protected by a single global latch to access the MVSG exclusively. In Oze, a transaction first searches the version list from the record from the latest version to find a readable version. A readable version is a committed version in which reading it does not create a cycle. If the transaction cannot find a readable version even after reaching the oldest version, it aborts itself. If there is a readable version, the transaction adds its txid to the read_follower in the txnode of the transaction that wrote the selected version, and adds the writer’s txids of the skipped versions to the write_follower in the own txnode (Lines 3–9). The record and the version are also added to the local read set and the read set on the graph, respectively (Lines 11–12).

When writing, a transaction in Oze creates a version and stores it in the local write set associated with the record (Lines 16–17). It processes the write set later in the global ordering phase to reduce unnecessary interferences on the records and the graph.

4.3 Global Ordering Phase

In the global ordering phase of Oze, a transaction verifies whether the serializability can be guaranteed while determining the order of transactions. Algorithm 3 shows the global ordering protocol. The centralized implementation uses a single global latch to exclusively access the MVSG throughout the entire ordering function.

For each record rec and version v in the local write set, the transaction first gets readers, a list of transactions reading the record, from the graph and adds postponing edges; the verifying transaction itself is placed behind in the serialization order (Lines 4–5). If there
within the same epoch to guarantee linearizability and simplify
reader’s
validates transactions in an optimistic way to achieve better perfor-
version order; we name it order forwarding because it forwards
performance and scalability. Specifically, it uses a loosely synchronized
MVSG by propagating the orders that each transaction has decided
to the MVSGs on each read/write record and the related records.

The key differences from the naive Oze protocol are
ordering() and
ordering(). In read() of the decentralized Oze, a transaction first
merges its local MVSG into the MVSG on the record. The process of
selecting the version and adding the reads-from edge is the same as
in Lines 2–14 of Algorithm 2 except that the merged graph is used
instead of the global MVSG. After selecting a version, it merges the
target graph on the record into the local one. write() is the same as the
centralized implementation because it does not access the MVSG.

The difference in the global ordering phase is shown in Algo-

4.4 Decentralized Graph Management

Protocols that use centralized graphs, such as MVSGT [20] and
MVSGA [19], have to take a single global latch whenever the graph
is updated, so they do not benefit from the recent many-core ar-
chitectures. Thus, the decentralized Oze manages the MVSG on
per-record basis instead of using a single centralized graph and
validates transactions in an optimistic way to achieve better perform-
and scalability. Specifically, it uses a loosely synchronized

| Algorithm 3: Global ordering phase |
|-----------------------------------|
| Function ordering(txn)            |
| // decided: List of txns ordered before committing txn (empty |
| when starting function)           |
| 1 Function ordering(txn)          |
| 2 for (rec, v) in txn.write_set do |
| 3 readers = find_readers(graph, rec) |
| 4 for r in readers do             |
| 5 graph[r.txid].write_follower.add(txn.txid) |
| 6 if is_acyclic(graph) then       |
| 7 decided.add(readers)            |
| 8 rec.insert_version([])          |
| 9 else                            |
| 10 followers = find_followers(graph, rec, readers) |
| 11 for r in readers do            |
| 12 graph[r.txid].write_follower.remove(txn.txid) |
| 13 if txn.txid.epoch == f.txid.epoch then |
| 14 graph[txn.txid].write_follower.add(f.txid) |
| 15 else                           |
| 16 abort()                        |
| 17 if is_acyclic(graph) then      |
| 18 rec.insert_version(followers)  |
| 19 else                           |
| 20 abort()                        |

| Algorithm 4: Global ordering in decentralized Oze |
|--------------------------------------------------|
| Function ordering(txn)                            |
| // done: List of records already processed (empty at beginning) |
| // target: List of records to be propagated (empty as well) |
| 1 Function ordering(txn)                          |
| 2 for (record, v) in write_set do                 |
| 3 merge(record.graph, txn.graph)                 |
| 4 (Omitted) // Same as lines 3–22 in Algorithm 3  |
| 5 add_target(record.graph, target, done)         |
| 6 merge(txn.graph, record.graph)                 |
| 7 done.add(record)                                |
| 8 target.insert(records in read_set)              |
| 9 while ! target.is_empty() do                    |
| 10 record = target.pop()                          |
| 11 merge(record.graph, txn.graph)                 |
| 12 if is_acyclic(graph) then                      |
| 13 abort()                                       |
| 14 add_target(txn, record.graph, target, done)    |
| 15 merge(txn.graph, record.graph)                 |
| 16 done.add(record)                               |
| 17 Function add_target(txn, graph, target, done)  |
| 18 followers = get_all_followers(txn, graph)      |
| 19 for follower in followers do                   |
| 20 for (rec, v) in graph[followers].read_set do    |
| 21 if rec not in done then                        |
| 22 target.add(rec)                                |

is no cycle, it adds readers to decided to remember that their order
is already fixed and inserts the version as the latest one (Lines 6–8).

If there is a cycle, to try a different version order, the transaction finds
followers that should be ordered after txn itself based on readers
(Line 10). Specifically, it lists followers by checking each reader’s
read set to observe which transaction (version) it is reading. Then,
it removes the current version order edges from readers to txn itself
except for the transactions already ordered and adds new preposing
edges from txn to each of followers (Line 13 and 16).

This edge replacement is equivalent to searching for another
version order; we name it order forwarding because it forwards
the transaction ahead in the serialization order. The order forwarding
itself can be performed across epochs. However, Oze limits it
within the same epoch to guarantee linearizability and simplify
graph cleaning (described in Section 4.6) and aborts transactions if
forwarding occurs across epochs (Lines 15–18).
the literature [2]. Since $T_1$ and $T_2$ write $y$ and $x$ that the other transactions read, both transactions visit $y$ and $x$ and select the version order in the global ordering, respectively. Then the order $T_1 < T_2$ and $T_2 < T_1$ are written for $x$ and $y$, since there is no cycle when postponing on each record. If Oze commits without resolving these inconsistent choices, the write skew would occur. To avoid it, Oze propagates and verifies the previously determined orders to each record in the read set (Line 11–12). If $T_1$ writes $T_2 < T_1$ on $x$ before $T_2$ writes the selected order ($T_1 < T_2$) on the same $x$, $T_2$ that comes later detects a cycle and aborts. That is, Oze is a first-come-first-win protocol. Note that both $T_1$ and $T_2$ might be aborted if they simultaneously write their choices to $y$ and $x$, respectively.

Correctness Sketch: Not only in the above case of two records and two transactions but also in the case of $n$ records and $n$ or more transactions, the decentralized Oze prevents any cycles such as write skews. As has been theoretically established in SSI [6, 16], the essence of those cycles is a series of anti-dependencies. Hence, using a similar idea, Oze can also guarantee serializability by finding propagation targets based on the anti-dependencies even if the MVSG is managed in a decentralized manner. If the validating transaction (for example, $T$) creates a cycle that includes $T$ itself, it must be due to a transaction that chooses an order following $T$; i.e., it must be a transaction that writes a record that $T$ reads as long as $T$ is still uncommitted. Thus, Oze never creates a cycle by guaranteeing that the transactions contained in $T$’s write_follower and its followers never precede $T$ through the propagation. In other words, Oze can guarantee serializability for the following reasons if it can propagate the orders to the record read by $T$’s subsequent transaction (Lines 17–22) without creating a cycle: (1) If a transaction is in-flight, the record is always revisited in the global ordering phase. Thus, it will be aborted if it precedes $T$ and creates a cycle. (2) If a transaction is in the global ordering phase, $T$ can confirm that the transaction does not precede $T$ (no cycle) since the read/write records have already been fixed.

Complexity: The dominant factor of the complexity in the decentralized Oze protocol is graph processing such as merging and cycle-checking. The time complexities of both processes are $O(|V| + |E|)$ where $|V|$ and $|E|$ are the number of nodes and edges in a graph$^3$, respectively. The graph processing must be done for each write records ($W$) and propagation records ($P$) which are read records and records found in the global ordering phase. Therefore, as a whole, the time complexity of the decentralized Oze protocol is $O((|W| + |P|)(|V| + |E|))$.

4.5 Parallel Validation

In the decentralized Oze, the cost of selecting, propagating, and verifying the version order in the global ordering phase increases, especially for a long transaction with many records to be read and written. In addition, there is a risk that the size of the graph will continue to grow due to the less frequent garbage collection during the processing of such long transactions, and the validation of the graph will continue forever. Thus, Oze performs the global ordering phase in parallel using multiple threads for fast validation.

The part that can be parallelized is the propagation phase (Lines 8–15 in Algorithm 4) after deciding the version order (4 Lines 2–6). If the validation threads (referred to as validators) do not know each other’s decision of the version orders, they cannot prevent the cycle of MVSG by propagation. Therefore, we only parallelize the propagation after determining the version orders.

4.6 Garbage Collection

This section describes the garbage collection (GC) of MVSG and record versions. In SGT [7], incoming edges are never added to a committed transaction; similarly, we can delete MVSG nodes that will never make a future cycle if we guarantee that there would be no additional incoming edge.

However, in Oze, incoming edges can be added to the committed transaction in two situations. The first case can occur in the read protocol. As mentioned in Section 4.2, when selecting a version to read, a reader transaction may add edges to the transactions (write_follower) that wrote the skipped version. The second case can occur in order forwarding when preposing a transaction, it adds edges to the write_follower transactions as mentioned in Section 4.3.

Oze uses epochs to guarantee that incoming edges are not added to a node anymore and delete it. An epoch that satisfies this condition is called reclamation_epoch ($e_r$), $e_r$ is the minimum local epoch of each worker thread minus one. We can prevent transactions from adding incoming edges that create a cycle by prohibiting (1) reading versions in $e_r$ or before (except the latest version) and (2) order forwarding to versions in $e_r$ or before.

Algorithm 5 shows the cleaning algorithm of the graph. First, for each $txnode$ before $e_r$, check if there is a newer transaction in thefollowers than $e_r$ (Lines 4–11). This prevents removing the $txnode$ read by the transaction in progress. If there is such a transaction, or if there is an incoming edge (i.e., from is not empty), the $txnode$ is excluded from GC targets (Lines 12–13). If $txnode$ is a GC target, delete its transaction ID from all followers (i.e., remove the incoming edge on the follower side), and then delete the node from the graph (Lines 14–16).

For GC of versions, we remove versions in $e_r$ or before except for the latest one (in the serialization order). We need to check the MVSG and hold versions where transactions are reading them.

5 EVALUATION

5.1 Experimental Setup

We evaluate Oze with BoMB that reproduces our targeting application workloads first and then report the performance of Oze on two standard benchmarks: TPC-C [12] and YCSB [9]. All experiments are performed using CCBench [34], a benchmark platform for various concurrency control protocols. We compare Oze with Silo [37], MOCC [39], TicToc [43], ERMIA [38], Cicada [25] and D2PL. D2PL is a 2PL-based protocol that mimics deterministic behavior such as in Calvin[36] and is only used for the static BoMB evaluation. D2PL first sorts all the accessing keys and then locks them in that order.

We use the original implementation of CCBench but modify it to support each workload efficiently; for instance, we unify the read/write interface and the abstract record format. We also implement Oze and D2PL in C++ as a new protocol on CCBench.
The evaluation environment consists of a single server with four Intel® Xeon® Platinum 8176 CPUs with 2.10 GHz processors and forty-eight DDR4-2666 32 GB DIMMs (total 1.5 TB). Each CPU has 28 physical cores and supports hyper-threading.

Similar to previous work [18], we evaluate all protocols in two modes: one-shot and interactive. The one-shot mode simulates situations in which all the necessary parameters are given at the beginning of a transaction and there is no interaction between the client and the database server. The interactive mode simulates situations in which the client executes transaction logic and sends requests to the database server. We emulate the interactive mode by inserting a 1-ms delay immediately after each request in the transaction logic of each workload.

5.2 Experiments on BoMB

We first evaluate how each protocol can handle the BoMB workload using static BoM (i.e., L1, S1 and S2 transactions only and BoM trees never change). Then, we run all six transactions of dynamic BoM only with Oze and D2PL based on the result of the static case.

5.2.1 L1 Transaction Runability. We run the L1, S1 and S2 transactions with one thread each for 1 minute while varying the number of target products from 20 to 100 and measure the throughput and abort rate of each type of transaction. We use the default parameters of BoMB shown in Table 1 except for varying products. Even with a high abort rate, the protocols may probabilistically commit the L1 transaction by increasing the number of trials, so we repeat the above ten times and calculate the success rate, the rate of successful trials that the L1 committed at least once. Figure 8 shows the success rate of the L1 and Figure 1 in Section 1 shows the average abort rate in these ten trials.

One-shot: For a large number of target products, no protocols can commit the L1 transaction other than Oze, MOCC and D2PL. Silo and TicToc abort almost all of the L1 transactions due to the reach validation failure in the commit phase because the S1 transactions update the cost of raw materials. Surprisingly, the multi-version protocols, ERMIA and Cicada can hardly commit the L1 transaction with even 20 products. As discussed in Section 2.5, with the benefit of multi-version, both ERMIA and Cicada can build the BoM trees and calculate the costs without being hindered by the S1. However, both protocols almost always abort the L1 as false positives since the writes of the costing results conflict with the reads of S2.

As for MOCC, the L1 can be committed with the following sensitive behavior. First, the L1 aborts if MOCC notices that a read happens with a larger number of products. Note that MOCC can easily abort the L1 if there are other concurrent S1 transactions. As for D2PL, its deterministic behavior allows it to acquire all locks without deadlocks and thus commit the L1.

Oze with 32 validators can commit the L1 perfectly for up to 140 products, but after that, it does not commit at all within the 1 minute. This is not due to the abort, but rather the ordering phase taking a long time to complete as a result of the size of the graph growing.

Interactive: The difference from the one-shot result is the behavior of MOCC and Oze with a single validator. For MOCC, since the number of trials for each type of transaction decreases due to

Algorithm 5: Graph cleaning in Oze

```
// followers: List of txns ordered after committing txn
1 Function clean(graph, reclamation_epoch)
2   for txnode in graph do
3       followers.clear()
4       if txnode.txid.epoch > reclamation_epoch then
5         continue
6       followers.add(txnode.read_follower)
7       followers.add(txnode.write_follower)
8       keep = false
9       for f in followers do
10          if f.epoch > reclamation_epoch then
11             keep = true; break
12       if keep or txnode.from.size() > 0 then
13          continue
14       for f in followers do
15          graph[f].from.remove(txnode.txid)
16       graph.remove(txnode)
```
the long read phase, accessing the same record consecutively as in the one-shot mode is less likely to occur. As a result, MOCC cannot commit the L1 even with 40 products. Regarding Oze, the local and global ordering phase is shortened because the graph growing speed is slower than that of the one-shot mode because of the fewer concurrent S1 transactions. Thus, Oze with the single validator can commit the L1 with a greater number of products.

5.2.2 Short Transaction Throughput. Figure 9 shows the average throughput of the short transaction (S1) during the above experiment. Note that it is not always appropriate to directly compare short transaction throughput from the viewpoint of whether they can handle heterogeneous workloads because long transactions cannot be committed at all except by Oze, MOCC and D2PL under certain conditions.

One-shot: While the existing protocols process roughly 50 to 100 Mtpm in the one-shot mode, Oze and D2PL process only a few Mtpm. The throughput of Oze with 32 validators decreases as the number of products increases. This is because the graph on the record, which is also handled by the short transactions, remains large for a long time without GC as a result of increasing the processing time of L1 transactions. For D2PL, short transactions that conflict with long transactions must wait to acquire locks, resulting in performance degradation with larger number of products.

Interactive: Unlike the one-shot mode, all protocols other than D2PL are almost comparable in the interactive mode. Because communication delay is added to the latency, the overhead of concurrency control (i.e., the performance difference) is small. However, only D2PL experiences significant performance degradation because the longer the L1 transaction continues to hold locks, the more the S1 transaction is affected by those locks.

5.2.3 Scalability Analysis of Oze. We evaluate the scalability of Oze by varying the number of threads for the short transactions.

We increase the number of threads for the S1 and S2 transactions up to 32 while keeping the L1 transaction on single thread. Figure 10 shows the throughput of the S1 transaction with 50 and 100 target-products. Note that we used 32 threads as validators and confirmed the L1 transaction could be committed in all cases.

In the one-shot mode, Oze shows near-linear scalability when the number of threads is small. The effect of parallelism reduces as the number of threads increases. As the size of graphs on records grow with more S1 transactions, the latency of the long transaction that accesses those records gradually becomes higher. The expansion of the graph size also affects the short transactions themselves since garbage collection is not triggered during the long transaction execution. The result of the interactive mode shows higher scalability than that of the one-shot mode while hiding the inserted delay because the size of the graph grows more gradually.

5.2.4 Parallel Validation. Figure 11 shows the throughput of the L1 transaction when increasing the number of validators from 1 to 64. In the one-shot mode, Oze cannot commit the L1 transaction with a single validator or even a small number of validation threads for 100 products, but it is possible to commit the L1 transaction using parallel validation, and its throughput increases with more threads. In the interactive mode, the effect of the parallel validation is smaller because the inserted delay extends the local ordering phase. Note that the benefit for both cases reduces as the number of threads increases threads because the parallel validation presents an overhead when merging the resulting graph of each validator and checking the acyclicity of the graph.

5.2.5 Dynamic Setting. Figure 12 shows the throughput of Oze and D2PL on dynamic BoM with varying product size. For Oze, each transaction runs with single worker thread and 32 validators. For D2PL, we only plot the L1 throughput since D2PL cannot commit it at all. D2PL issues reconnaissance queries [36] to determine input records, which are locked and validated at actual execution time. However, D2PL always fails to lock or validate them since the inputs change dynamically. In contrast, Oze can handle all types of transactions. Note that the overall throughput decreased as the number of products increased, because of the size of the graph growing in the L1 transaction. Especially, the S2 throughput drops significantly if the S2 transaction finds the L1 transaction in the graph which causes the large number of propagation.
Figure 13: TPC-C-NP throughput.

5.3 Experiments on TPC-C

We compare Oze with other concurrency control protocols on the TPC-C benchmark. We only run New-Order and Payment transactions with the same ratio since they account for a large percentage of full-mixed queries of TPC-C.

Figure 13 shows the throughput of each protocol with varying number of threads and warehouses. The throughput of Oze in the one-shot mode is an order of magnitude slower, but the throughput in the interactive mode is comparable to other protocols and scales almost linearly. This is because the overhead of concurrency control is masked by the delay. Unfortunately, we do not see advantages of using Oze for workloads such as TPC-C, where long and short transactions do not mix at the same time. We could switch between Oze and other protocols if it is guaranteed that such mixing does not occur only at a certain time.

5.4 Experiments on YCSB

We present empirical evaluation with YCSB to understand the details of Oze’s protocol behavior. We run YCSB-A (50% reads and 50% pure writes) for 100 million records with 100 bytes payloads. The number of Oze worker threads is 28 and all workers use the single-thread validation. Figure 14 shows the throughput and the average graph size with (a) varying number of operations in a transaction and (b) varying skew. Note that the graph size is the average number of nodes in cycle checking.

As shown in the analysis of computational complexity in Section 4.4, the throughput is almost inversely proportional to the product of the number of operations (i.e., write records and propagated records) and the graph size when there is no skew. When the skew exceeds 0.7, the graph size increases dramatically, and the throughput drops by an order of magnitude.

Figure 15 shows the average latency required to process each major function of Oze. Both Figure 15 (a) and (b) show that the percentage of propagation becomes larger compared to read processing (e.g., cycle check) and version ordering (i.e., determining version orders) as the graph size increases. Therefore, reducing the graph size with more sophisticated garbage collection is one of the major challenges in the successor of Oze.

6 RELATED WORK

Benchmark: TPC-C [12] is the de facto standard benchmark for OLTP systems that simulates a warehouse-centric order processing application. TPC-E [13] simulates the activity of processing brokerage trades. Though TPC-C and TPC-E provide realistic workloads, both lack long transactions with update operations, which BoMB provides. TPC-EH [38] is a variant of TPC-E and has a read-mostly (i.e., write-included) long transaction. However, there is no transaction that reads the result (Asset-History) written by the read-mostly long transaction, which corresponds to the S2 transaction in BoMB. YCSB [9] provides synthetic workloads comprised of homogeneous operations to benchmark cloud services.

Lock-based Protocols: In 2PL variants using timestamp-based priority [10, 18, 31], a long transaction can commit when it has the smallest timestamp. Then, subsequent short transactions must either wait or abort until the long one commits if they conflict with the long transaction. Altruistic locking [32] enables transactions to donate objects which have been locked and permitted other transactions to access the donated objects before they are unlocked. Once short transactions (e.g., S1) accept a donation, they must wait for another donation to access another record regardless of whether long transactions use them, which increases the waiting time.

Protocols for Highly-Contended Workloads: ERMIA [42] and Cicada [25] keep multiple versions to handle highly-contended workloads. MOCC [39] and ACC [35] are hybrid protocols that switch between an optimistic and a pessimistic scheme to avoid starvation. Commit-time updates and timestamp splitting [22] avoid the high contention using the database schema and the workload knowledge. A batching and reordering scheme [14] is for contended workloads with flexibility. While highly-contended workloads have been explored, heterogeneous workloads with long-running update transactions, such as BoMB, have been less discussed.

Deterministic Databases: Calvin [36] executes transactions while acquiring locks based on the pre-determined total order. This behavior is the same as D2PL and would not work for dynamic
We proposed Oze, a new concurrency control protocol that exploits a large scheduling space using a fully precise multi-version serialization graph in a decentralized manner. We also proposed a new OLTP benchmark, BoMB, based on a use case in an actual manufacturing company. Experiments using BoMB showed that Oze keeps the abort rate of the long-running update transaction at zero while reaching up to 1.7 Mtpm for short transactions with near-linear scalability, whereas state-of-the-art protocols cannot commit the long transaction or experience performance degradation in short transaction throughput.

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