Information Systems
(Informationssysteme)

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Part VIII

Transaction Management

The "Hello World" of Transaction Management

- My bank issued me a debit card to access my account.
- Every once in a while, I'd use it at an ATM to draw some money from my account, causing the ATM to perform a **transaction** in the bank's database.

$bal \leftarrow$ **read_bal** $(acct\_no)$;
$bal \leftarrow bal - 100\,\text{EUR}$;
write_bal $(acct\_no, bal)$;

- My account is properly updated to reflect the new balance.

Concurrent Access

The problem is: My wife has a card for the account, too.

- We might end up using our cards at different ATMs at the **same time**.

me	**my wife**	**DB state**
$bal \leftarrow \texttt{read}\,(acct)\,;$		1200
	$bal \leftarrow \texttt{read}\,(acct)\,;$	1200
$bal \leftarrow bal - 100\,;$		1200
	$bal \leftarrow bal - 200\,;$	1200
$\texttt{write}\,(acct, bal)\,;$		1100
	$\texttt{write}\,(acct, bal)\,;$	1000

- The first update was **lost** during this execution. Lucky me!

Another Example

- This time, I want to **transfer** money over to another account.

```
  // Subtract money from source (checking) account
1 chk_bal ← read_bal (chk_acct_no) ;
2 chk_bal ← chk_bal − 500 EUR ;
3 write_bal (chk_acct_no, chk_bal) ;
  // Credit money to the target (saving) account
4 sav_bal ← read_bal (sav_acct_no) ;
5 sav_bal ← sav_bal + 500 EUR ;
6 write_bal (sav_acct_no, sav_bal) ;
```

- Before the transaction gets to step **6**, its execution is **interrupted or cancelled** (power outage, disk failure, software bug, ...). My money is **lost** ☹.

ACID Properties

One of the key benefits of a database system are the **transaction properties** guaranteed to the user:

A	Atomicity	Either **all** or **none** of the updates in a database transaction are applied.
C	Consistency	Every transaction brings the database from one **consistent** state to another.
I	Isolation	A transaction must not see any effect from other transactions that run in parallel.
D	Durability	The effects of a **successful** transaction maintain persistent and may not be undone for system reasons.

A challenge is to preserve these guarantees even with **multiple users** accessing the database **concurrently**.

Anomalies: Lost Update

- We already saw a **lost update** example on slide 257.
- The effects of one transaction are lost, because of an uncontrolled overwriting by the second transaction.

Anomalies: Inconsistent Read

Consider the money transfer example (slide 258), expressed in SQL syntax:

Transaction 1	Transaction 2
`UPDATE Accounts SET balance = balance - 500 WHERE customer = 4711 AND account_type = 'C';`	
	`SELECT SUM(balance) FROM Accounts WHERE customer = 4711;`
`UPDATE Accounts SET balance = balance + 500 WHERE customer = 4711 AND account_type = 'S';`	

- Transaction 2 sees an **inconsistent** database state.

Anomalies: Dirty Read

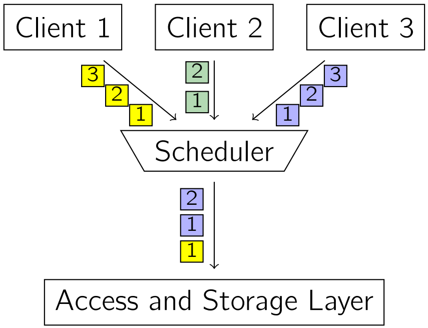
At a different day, my wife and me again end up in front of an ATM at roughly the same time:

me	**my wife**	**DB state**
$bal \leftarrow$ `read` $(acct)$;		1200
$bal \leftarrow bal - 100$;		1200
`write` $(acct, bal)$;		1100
	$bal \leftarrow$ `read` $(acct)$;	1100
	$bal \leftarrow bal - 200$;	1100
`abort` ;		1200
	`write` $(acct, bal)$;	900

- My wife's transaction has already read the modified account balance before my transaction was **rolled back**.

Concurrent Execution

- The **scheduler** decides the execution order of concurrent database accesses.



Database Objects and Accesses

We now assume a slightly simplified model of database access:

1. A database consists of a number of named **objects**. In a given database state, each object has a **value**.
2. Transactions access an object o using the two operations `read` o and `write` o.

In a **relational** DBMS we have that

$$\text{object} \equiv \text{tuple} \quad .$$

Transactions

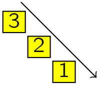
A **database transaction** T is a (strictly ordered) sequence of **steps**. Each **step** is a pair of an **access operation** applied to an **object**.

- Transaction $T = \langle s_1, \ldots, s_n \rangle$
- Step $s_i = (a_i, e_i)$
- Access operation $a_i \in \{\texttt{r(ead)}, \texttt{w(rite)}\}$

The **length** of a transaction T is its number of steps $|T| = n$.

We could write the money transfer transaction as

$$T = \langle\ (\texttt{read}, \mathit{Checking}), (\texttt{write}, \mathit{Checking}), (\texttt{read}, \mathit{Saving}), (\texttt{write}, \mathit{Saving})\ \rangle$$



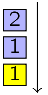
or, more concisely,

$$T = \langle r(C), w(C), r(S), w(S) \rangle \ .$$

Schedules

A **schedule** S for a given set of transactions $\mathbf{T} = \{T_1, \ldots, T_n\}$ is an arbitrary sequence of execution steps

$$S(k) = (T_j, a_i, e_i) \qquad k = 1 \ldots m \ ,$$



such that

1. S contains all steps of all transactions and nothing else and
2. the order among steps in each transaction T_j is preserved:
$$(a_p, e_p) < (a_q, e_q) \text{ in } T_j \Rightarrow (T_j, a_p, e_p) < (T_j, a_q, e_q) \text{ in } S \ .$$

We sometimes write

$$S = \langle r_1(B), r_2(B), w_1(B), w_2(B) \rangle$$

to mean

$$S(1) = (T_1, \texttt{read}, B) \quad S(3) = (T_1, \texttt{write}, B)$$
$$S(2) = (T_2, \texttt{read}, B) \quad S(4) = (T_2, \texttt{write}, B)$$

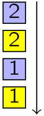
Serial Execution

One particular schedule is **serial execution**.

- A schedule S is **serial** iff, for each contained transaction T_j, all its steps follow each other (no interleaving of transactions).

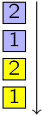
Consider again the ATM example from slide 257.

- $S = \langle r_1(B), r_2(B), w_1(B), w_2(B) \rangle$
- This schedule is **not** serial.



If my wife had gone to the bank one hour later, "our" schedule probably would have been serial.

- $S = \langle r_1(B), w_1(B), r_2(B), w_2(B) \rangle$



Correctness of Serial Execution

- Anomalies such as the "lost update" problem on slide 257 can **only** occur in multi-user mode.
- If all transactions were fully executed one after another (no concurrency), no anomalies would occur.
- **Any serial execution is correct.**

- Disallowing concurrent access, however, is **not practical**.
- Therefore, allow concurrent executions if they are **equivalent** to a serial execution.

Conflicts

What does it mean for a schedule S to be equivalent to another schedule S'?

- Sometimes, we may be able to **reorder** steps in a schedule.
  - We must not change the order among steps of any transaction T_j (↗ slide 266).
  - Rearranging operations must not lead to a different **result**.
- Two operations (a, e) and (a', e') are said to be **in conflict** $(a, e) \nleftrightarrow (a', e')$ if their order of execution matters.
  - When reordering a schedule, we must not change the relative order of such operations.
- Any schedule S' that can be obtained this way from S is said to be **conflict equivalent** to S.

Conflicts

Based on our `read`/`write` model, we can come up with a more machine-friendly definition of a conflict.

- Two operations (T_i, a, e) and (T_j, a', e') are **in conflict** in S if
  1. they belong to two **different transactions** $(T_i \neq T_j)$,
  2. they access the **same database object**, *i.e.*, $e = e'$, and
  3. at least one of them is a `write` operation.
- This inspires the following conflict matrix:

	`read`	`write`
`read`		×
`write`	×	×

- **Conflict relation $\prec_S$:**

$$(T_i, a, e) \prec_S (T_j, a', e')$$
$$:=$$
$$(a, e) \not\leftrightarrow (a', e') \wedge (T_i, a, e) \text{ occurs before } (T_j, a', e') \text{ in } S \wedge T_i \neq T_j$$

Conflict Serializability

- A schedule S is **conflict serializable** iff it is conflict equivalent to **some** serial schedule S'.
- **The execution of a conflict-serializable S schedule is correct.**
  - S does **not** have to be a serial schedule.

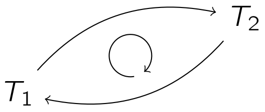
- This allows us to **prove** the correctness of a schedule S based on its **conflict graph** $G(S)$ (also: **serialization graph**).
  - **Nodes** are all transactions T_i in S.
  - There is an **edge** $T_i \rightarrow T_j$ iff S contains operations (T_i, a, e) and (T_j, a', e') such that $(T_i, a, e) \prec_S (T_j, a', e')$.
- S is conflict serializable if $G(S)$ is **acyclic**.[13]

[13] A serial execution of S could be obtained by sorting $G(S)$ **topologically**.

Serialization Graph

Example: ATM transactions (↗ slide 257)

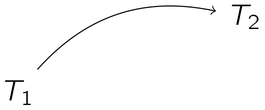
- $S = \langle r_1(A), r_2(A), w_1(A), w_2(A) \rangle$
- Conflict relation:
  $(T_1, \mathtt{r}, A) \prec_S (T_2, \mathtt{w}, A)$
  $(T_2, \mathtt{r}, A) \prec_S (T_1, \mathtt{w}, A)$
  $(T_1, \mathtt{w}, A) \prec_S (T_2, \mathtt{w}, A)$



→ **not** serializable

Example: Two money transfers (↗ slide 258)

- $S = \langle r_1(C), w_1(C), r_2(C), w_2(C), r_1(S), w_1(S), r_2(S), w_2(S) \rangle$
- Conflict relation:
  $(T_1, \mathtt{r}, C) \prec_S (T_2, \mathtt{w}, C)$
  $(T_1, \mathtt{w}, C) \prec_S (T_2, \mathtt{r}, C)$
  $(T_1, \mathtt{w}, C) \prec_S (T_2, \mathtt{w}, C)$
  ⋮



→ serializable

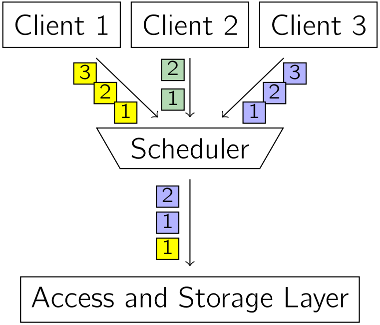
Query Scheduling

Can we build a scheduler that **always** emits a serializable schedule?

Idea:

- Require each transaction to obtain a **lock** before it accesses a data object *o*:

```
lock o ;
...access o ...;
unlock o ;
```



- This prevents **concurrent** access to *o*.

Locking

- If a lock cannot be granted (*e.g.*, because another transaction T' already holds a **conflicting** lock) the requesting transaction T_i gets **blocked**.
- The scheduler **suspends** execution of the blocked transaction T.
- Once T' **releases** its lock, it may be granted to T, whose execution is then **resumed**.
- Since other transactions can continue execution while T is blocked, locks can be used to **control the relative order of operations**.

Locking and Serializability

✎ **Does locking guarantee serializable schedules, yet?**

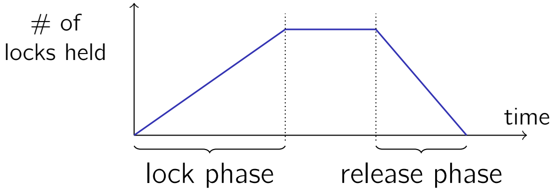
ATM Transaction with Locking

Transaction 1	Transaction 2	DB state
`lock (acct) ;`		1200
`read (acct) ;`		
`unlock (acct) ;`		
	`lock (acct) ;`	
	`read (acct) ;`	
	`unlock (acct) ;`	
`lock (acct) ;`		
`write (acct) ;`		1100
`unlock (acct) ;`		
	`lock (acct) ;`	
	`write (acct) ;`	1000
	`unlock (acct) ;`	

Two-Phase Locking (2PL)

The **two-phase locking protocol** poses an additional restriction:

- Once a transaction has **released** any lock, it must **not** acquire any new lock.



- Two-phase locking is **the** concurrency control protocol used in database systems today.

Again: ATM Transaction

Transaction 1	Transaction 2	DB state
`lock` (*acct*) ;		1200
`read` (*acct*) ;		
`unlock` (*acct*) ;		
	`lock` (*acct*) ;	
	`read` (*acct*) ;	
	`unlock` (*acct*) ;	
`lock` (*acct*) ; ↯		
`write` (*acct*) ;		1100
`unlock` (*acct*) ;		
	`lock` (*acct*) ; ↯	
	`write` (*acct*) ;	1000
	`unlock` (*acct*) ;	

A 2PL-Compliant ATM Transaction

- To comply with the two-phase locking protocol, the ATM transaction must not acquire any new locks after a first lock has been released.

```
lock (acct) ;
bal ← read_bal (acct) ;
bal ← bal − 100 EUR ;
write_bal (acct, bal) ;
unlock (acct) ;
```

} lock phase

} unlock phase

Resulting Schedule

Transaction 1	Transaction 2	DB state
`lock` (*acct*) ;		1200
`read` (*acct*) ;		
	`lock` (*acct*) ;	
`write` (*acct*) ;	↓ Transaction	1100
`unlock` (*acct*) ;	blocked	
	`read` (*acct*) ;	
	`write` (*acct*) ;	900
	`unlock` (*acct*) ;	

- The use of locking lead to a correct (and serializable) schedule.

Deadlocks

- Like many lock-based protocols, two-phase locking has the risk of **deadlock** situations:

Transaction 1	**Transaction 2**
`lock` (A) ;	
⋮	`lock` (B)
do something	⋮
⋮	do something
`lock` (B)	⋮
[wait for T_2 to release lock]	`lock` (A)
	[wait for T_1 to release lock]

- Both transactions would wait for each other **indefinitely**.

Deadlock Handling

A typical approach to deal with deadlocks is **deadlock detection**:

- The system maintains a **waits-for graph**, where an edge $T_1 \rightarrow T_2$ indicates that T_1 is blocked by a lock held by T_2.
- Periodically, the system tests for **cycles** in the graph.
- If a cycle is detected, the deadlock is **resolved** by **aborting** one or more transactions.
- Selecting the **victim** is a challenge:
  - Blocking **young** transactions may lead to **starvation**: the same transaction is cancelled again and again.
  - Blocking an **old** transaction may cause a lot of investment to be thrown away.

Deadlock Handling

Other common techniques:

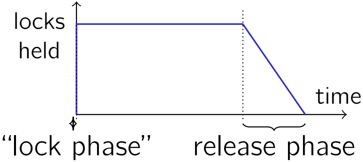
- **Deadlock prevention:** *e.g.*, by treating handling lock requests in an **asymmetric** way:
  - **wait-die**: A transaction is never blocked by an **older** transaction.
  - **wound-wait**: A transaction is never blocked by a **younger** transaction.
- **Timeout:** Only wait for a lock until a timeout expires. Otherwise assume that a deadlock has occurred and **abort**.

E.g., IBM DB2 UDB:

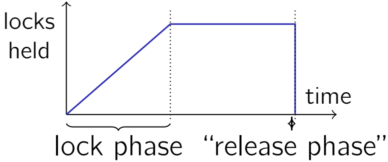
```
db2 => GET DATABASE CONFIGURATION;
  :
  :
Interval for checking deadlock (ms)      (DLCHKTIME) = 10000
Lock timeout (sec)                     (LOCKTIMEOUT) = -1
```

Variants of Two-Phase Locking

- The two-phase locking protocol does not prescribe exactly when locks have to acquired and released.
- Possible variants:



preclaiming 2PL

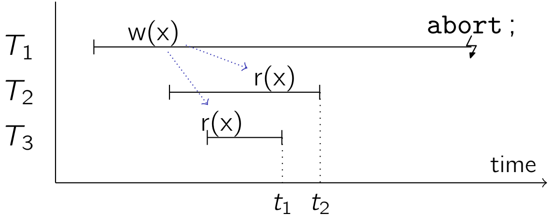


strict 2PL

- ✎ **What could motivate either variant?**

Cascading Rollbacks

Consider three transactions:



- When transaction T_1 aborts, transactions T_2 and T_3 have already read data written by T_1 (↗ dirty read, slide 262)
- T_2 and T_3 need to be **rolled back**, too.
- T_2 and T_3 **cannot** commit until the fate of T_1 is known.
- This problem cannot arise under strict two-phase locking.

Consistency Guarantees and SQL 92

Sometimes, some degree of inconsistency may be acceptable for specific applications:

- “Mistakes” in few data sets, *e.g.*, will not considerably affect the outcome of an aggregate over a huge table.
  - ⇝ Inconsistent read anomaly
- SQL 92 specifies different **isolation levels**.
- *E.g.*,

```
SET ISOLATION SERIALIZABLE;
```

- Obviously, less strict consistency guarantees should lead to increased throughput.

SQL 92 Isolation Levels

read uncommitted (also: 'dirty read' or 'browse')
: Only **write locks** are acquired (according to strict 2PL).

read committed (also: 'cursor stability')
: **Read locks** are only held for as long as a cursor sits on the particular row. **Write locks** acquired according to strict 2PL.

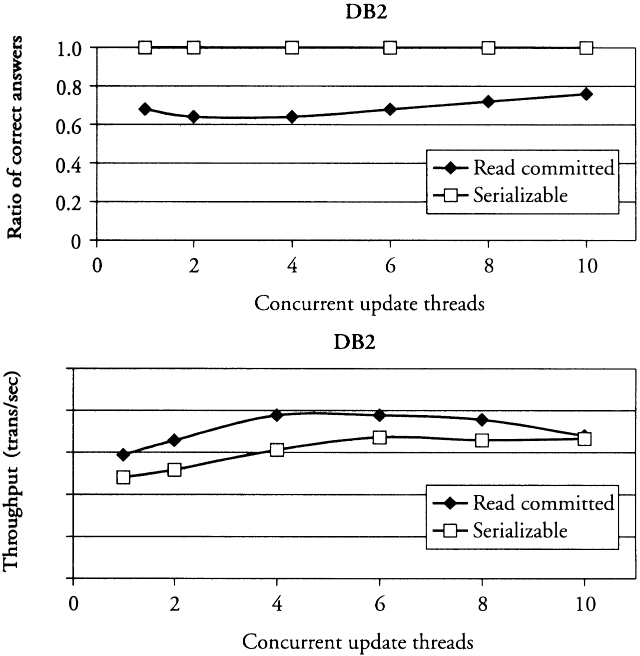
repeatable read (also: 'read stability')
: Acquires **read** and **write locks** according to strict 2PL.

serializable
: Additionally obtains locks to avoid **phantom reads**.

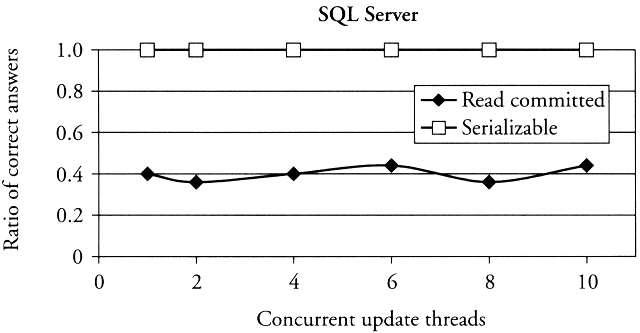
Phantom Problem

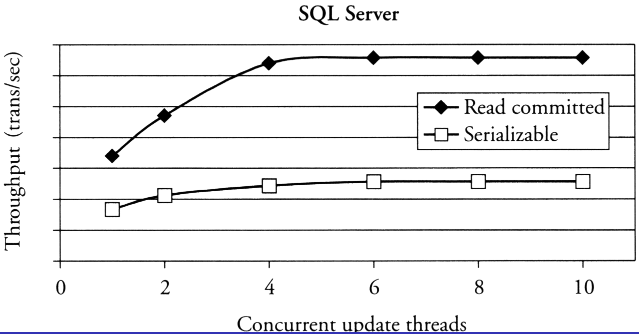
Transaction 1	Transaction 2	Effect
scan relation R ;		T_1 locks all rows
	insert new row into R ;	T_2 locks new row
	`commit` ;	T_2's lock released
scan relation R ;		reads **new** row, too!

- Although both transactions properly followed the 2PL protocol, T_1 observed an effect caused by T_2.
- Cause of the problem: T_1 can only lock **existing** rows.
- Possible solutions:
  - **Key range locking**, typically in B-trees
  - **Predicate locking**



Dennis Shasha nad Philippe Bonnet. Database Tuning. Morgan Kaufmann, 2003.





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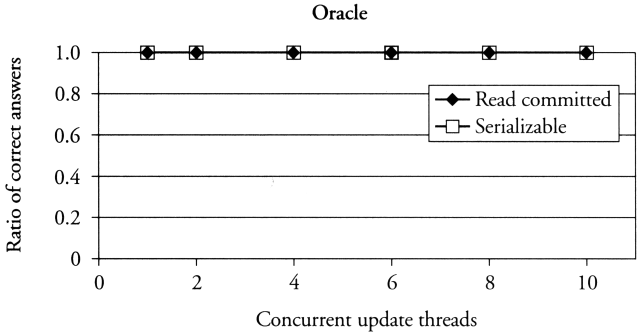

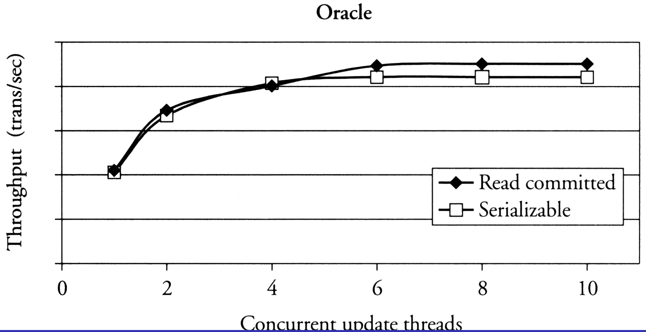

Dennis Shasha nad Philippe Bonnet. Database Tuning. Morgan Kaufmann, 2003.

Resulting Consistency Guarantees

isolation level	dirty read	non-repeat. rd	phantom rd
read uncommitted	possible	possible	possible
read committed	not possible	possible	possible
repeatable read	not possible	not possible	possible
serializable	not possible	not possible	not possible

- Some implementations support more, less, or different levels of isolation.
- Few applications really need serializability.

Optimistic Concurrency Control

- So far we've been rather **pessimistic**:
  - we've assumed the worst and prevented that from happening.
- In practice, conflict situations are not that frequent.
- **Optimistic concurrency control:** Hope for the best and only act in case of conflicts.

Optimistic Concurrency Control

Handle transactions in **three phases**:

1. **Read Phase.** Execute transaction, but do **not** write data back to disk immediately. Instead, collect updates in a **private workspace**.
2. **Validation Phase.** When the transaction wants to **commit**, test whether its execution was correct. If it is not, **abort** the transaction.
3. **Write Phase.** Transfer data from private workspace into database.

Validating Transactions

Validation is typically implemented by looking at transactions'

- **Read Sets** $RS(T_i)$**:** (attributes read by transaction T_i) and
- **Write Sets** $WS(T_i)$**:** (attributes written by transaction T_i).

backward-oriented optimistic concurrency control (BOCC):

Compare T against all **committed** transactions T_c.
Check **succeeds** if

$$T_c \text{ committed before } T \text{ started} \quad \textbf{or} \quad RS(T) \cap WS(T_c) = \varnothing \ .$$

forward-oriented optimistic concurrency control (FOCC):

Compare T against all **running** transactions T_r.
Check **succeeds** if

$$WS(T) \cap RS(T_r) = \varnothing \ .$$

Multiversion Concurrency Control

Consider the schedule

$$r_1(x), w_1(x), r_2(x), \overset{\color{red}{t \atop \downarrow}}{} w_2(y), r_1(y), w_1(z) \ .$$

✎ **Is this schedule serializable?**

- Now suppose when T_1 wants to read y, we'd still have the "old" value of y, valid at time t, around.
- We could then create a history equivalent to

$$r_1(x), w_1(x), r_2(x), r_1(y), w_2(y), w_1(z) \ ,$$

which is **serializable**.

Multiversion Concurrency Control

- With old **object versions** still around, **read** transactions need no longer be blocked.
- They might see **outdated, but consistent** versions of data.
- **Problem:** Versioning requires **space** and **management overhead** ($\rightsquigarrow$ garbage collection).

- Some systems support **snapshot isolation**.
  - Oracle, SQL Server, PostgreSQL