第10章：并发控制

Concurrency Control

邹兆年

哈尔滨工业大学
计算机科学与技术学院
海量数据计算研究中心
电子邮件：znzou@hit.edu.cn

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教学内容[1]

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Transactions

事务(Transactions)

事务(transaction)是在数据库上执行的一个或多个操作构成的序列，用来完成数据库系统的高级功能

- 事务的操作要么全部执行，要么一个也不执行

Example (转账事务)

账户A给账户B转账100元

1. 检查账户A余额是否够100元
2. 从账户A中减去100元
3. 在账户B中增加100元

SQL事务语句(Transactional Statements)

事务启动(start): `BEGIN;`

事务提交(commit): `COMMIT;`

- 将事务对数据库的修改持久地写到数据库中

事务中止(abort): `ROLLBACK;`

- 将事务对数据库的修改全部撤销(undo)，就像事务从未执行过
- 事务可以中止自己，也可以被DBMS中止

演示

```
CREATE TABLE t (
  id INT PRIMARY KEY,
  val INT NOT NULL
);

SET autocommit=OFF;
```

事务的ACID性质(The ACID Properties)

原子性(Atomicity):"all or nothing"

- 事务的操作要么全部执行，要么一个也不执行

一致性(Consistency):"it looks correct to me"

- 如果事务的程序正确，并且事务启动时数据库处于一致状态(consistent state)，则事务结束时数据库仍处于一致状态

隔离性(Isolation):"as if alone"

- 一个事务的执行不受其他事务的干扰

持久性(Durability):"survive failures"

- 事务一旦提交，它对数据库的修改一定全部持久地写到数据库中

原子性(Atomicity)

"All or Nothing"

事务的执行只有两种结局

- 执行完所有操作后提交$\Longrightarrow$ 不破坏原子性
- 执行了部分操作后中止$\Longrightarrow$ 破坏原子性

DBMS保证事务的原子性

- 中止事务(aborted txn)执行过的操作必须撤销(undo)

第12章: 故障恢复(Crash Recovery)

持久性(Durability)

"Survive Failures"

故障(failure)导致事务对数据库的修改有4种结果

- 提交事务的修改已全部持久存储$\Longrightarrow$ 不破坏持久性
- 提交事务的修改仅部分持久存储$\Longrightarrow$ 破坏持久性
- 中止事务的修改有些已持久存储$\Longrightarrow$ 破坏持久性
- 中止事务的修改未持久存储$\Longrightarrow$ 不破坏持久性

DBMS保证事务的持久性

- 重做(redo)提交事务对数据库的修改
- 撤销(undo)中止事务对数据库的修改

第12章: 故障恢复(Failure Recovery)

一致性(Consistency)

"It Looks Correct to Me"

用户(user)保证事务的一致性

- 别写错程序

隔离性(Isolation)

"As If Alone"

多个事务的执行有2种方式

- 串行执行(serial execution) $\Longrightarrow$ 不破坏隔离性
- 交叉执行(interleaving execution) $\Longrightarrow$ 可能破坏隔离性

DBMS保证事务的隔离性

- 并发控制(concurrency control): 确定多个事务的操作的正确交叉执行顺序

第11章: 并发控制(Concurrency Control)

Concurrency Control

Concurrency Control
Schedules

基本概念

数据库(database): 固定的数据对象集合(a fixed set of data objects)

- 数据对象是个抽象概念，可以是属性值、元组、页、关系或数据库
- 数据对象又称数据库元素(database element)
- 我们先不考虑数据的插入和删除

事务(transaction): 数据库对象的读/写操作序列

- 事务可以在数据库上进行很多操作，但DBMS只关心事务对数据对象的读/写操作

调度(Schedules)

调度(schedule)是一个或多个事务的重要操作(action)的序列

Example (调度)

T_1	T_2
READ(A, t)	
	READ(A, s)
t := t + 100	
	s := s * 2
WRITE(A, t)	
	WRITE(A, s)
READ(B, t)	
	READ(B, s)
t := t + 100	
	s := s * 2
WRITE(B, t)	
	WRITE(B, s)

串行调度(Serial Schedules)

如果一个调度中不同事务的操作没有交叉(interleave)，则该调度是串行调度(serial schedule)

Example (串行调度)

T_1	T_2
READ(A, t)	
t := t + 100	
WRITE(A, t)	
READ(B, t)	
t := t + 100	
WRITE(B, t)	
	READ(A, s)
	s := s * 2
	WRITE(A, s)
	READ(B, s)
	s := s * 2
	WRITE(B, s)

T_1	T_2
	READ(A, s)
	s := s * 2
	WRITE(A, s)
	READ(B, s)
	s := s * 2
	WRITE(B, s)
READ(A, t)	
t := t + 100	
WRITE(A, t)	
READ(B, t)	
t := t + 100	
WRITE(B, t)	

非串行调度(Nonserial Schedules)

不是串行调度的调度称为非串行调度(nonserial schedule)

Example (非串行调度)

T_1	T_2
READ(A, t)	
t := t + 100	
WRITE(A, t)	
	READ(A, s)
	s := s * 2
	WRITE(A, s)
READ(B, t)	
t := t + 100	
WRITE(B, t)	
	READ(B, s)
	s := s * 2
	WRITE(B, s)

T_1	T_2
READ(A, t)	
	READ(A, s)
t := t + 100	
	s := s * 2
WRITE(A, t)	
	WRITE(A, s)
READ(B, t)	
	READ(B, s)
t := t + 100	
	s := s * 2
WRITE(B, t)	
	WRITE(B, s)

调度的正确性(Correctness of Schedules)

每个事务孤立执行(executed in isolation)，都会将数据库从一种一致性状态(consistent state)变为另一种一致性状态

Example (The Correctness Principle)

设数据库的一致性约束条件(consistency constraint)为 $A = B$

T_1	A	B
	25	25
READ(A, t)		
t := t + 100		
WRITE(A, t)	125	
READ(B, t)		
t := t + 100		
WRITE(B, t)		125

T_2	A	B
	25	25
READ(A, s)		
s := s * 2		
WRITE(A, s)	50	
READ(B, s)		
s = s * 2		
WRITE(B, s)		50

任意串行调度都能保持数据库的一致性

Example (Correct Serial Schedules)

T_1	T_2	A	B
		25	25
READ(A, t)			
t := t + 100			
WRITE(A, t)		125	
READ(B, t)			
t := t + 100			
WRITE(B, t)			125
	READ(A, s)		
	s := s * 2		
	WRITE(A, s)	250	
	READ(B, s)		
	s := s * 2		
	WRITE(B, s)		250

不同的串行调度可能导致数据库处于不同的最终状态，但都是一致状态

Example (Correct Serial Schedules)

T_1	T_2	A	B
		25	25
	READ(A, s)		
	s := s * 2		
	WRITE(A, s)	50	
	READ(B, s)		
	s := s * 2		
	WRITE(B, s)		50
READ(A, t)			
t := t + 100			
WRITE(A, t)		150	
READ(B, t)			
t := t + 100			
WRITE(B, t)			150

非串行调度可能会破坏数据库的一致性

Example (Incorrect Nonserial Schedules)

T_1	T_2	A	B
		25	25
READ(A, t)			
t := t + 100			
WRITE(A, t)		125	
	READ(A, s)		
	s := s * 2		
	WRITE(A, s)	250	
	READ(B, s)		
	s := s * 2		
	WRITE(B, s)		50
READ(B, t)			
t := t + 100			
WRITE(B, t)			150

异常(Anomalies)

非串行调度会导致事务的异常行为(anomaly behavior)，从而破坏数据库的一致性

- 脏写(Dirty Writes/Overwriting Uncommitted Data)
- 脏读(Dirty Reads/Reading Uncommited Data)
- 不可重复读(Unrepeatable Reads)
- 幻读(Phantoms)

脏写(Dirty Writes/Overwriting Uncommitted Data)

The value of A written by T_1 is overwritten by T_2 before T_1 commits

Example (脏写)

T_1	T_2	A	B
		25	25
READ(A, t)			
t := t + 100			
	READ(A, s)		
	s := s * 2		
	WRITE(A, s)	50	
WRITE(A, t)		125	
	READ(B, s)		
	s := s * 2		
READ(B, t)			
t := t + 100			
WRITE(B, t)			125
	WRITE(B, s)		50

脏读(Dirty Reads/Reading Uncommited Data)

The value of A written by T_1 is read by T_2 before T_1 commits

Example (脏读)

T_1	T_2	A	B
		25	25
READ(A, t)			
t := t + 100			
WRITE(A, t)		125	
	READ(A, s)		
	s := s * 2		
	WRITE(A, s)	250	
	READ(B, s)		
	s := s * 2		
	WRITE(B, s)		50
READ(B, t)			
t := t + 100			
WRITE(B, t)			150

不可重复读(Unrepeatable Reads)

- T_2 changes the value of A that has been read by T_1, and T_2 commits
- If T_1 tries to read the value of A again, it will get a different result, even though T_1 has not modified A in the meantime

Example (不可重复读)

设一致性约束条件为$A \geq 0$

T_1	T_2	A
		1
READ(A, t)		
	READ(A, s)	
	s := s - 1	
	WRITE(A, s)	0
READ(A, t)		
t := t - 1		
WRITE(A, t)		-1

幻读(Phantoms)

涉及数据的插入和删除，后面再讲

演示

```
CREATE TABLE t (
  id INT PRIMARY KEY,
  val INT NOT NULL
);

SET autocommit=OFF;
```


等价调度(Equivalent Schedules)

如果两个调度在任意数据库实例上的效果都相同，则等价(equivalent)

Example (等价调度)

T_1	T_2	A	B	T_1	T_2
		25	25		
READ(A, t)				READ(A, t)	
t := t + 100				t := t + 100	
WRITE(A, t)		125		WRITE(A, t)	
	READ(A, s)			READ(B, t)	
	s := s * 2			t := t + 100	
	WRITE(A, s)	250		WRITE(B, t)	
READ(B, t)					READ(A, s)
t := t + 100					s := s * 2
WRITE(B, t)			125		WRITE(A, s)
	READ(B, s)				READ(B, s)
	s := s * 2				s := s * 2
	WRITE(B, s)		250		WRITE(B, s)

可串行化调度(Serializable Schedules)

如果一个调度等价于某串行调度，则该调度是可串行化调度(serializable schedule)

Example (可串行化调度)

T_1	T_2	A	B	T_1	T_2
		25	25		
READ(A, t)				READ(A, t)	
t := t + 100				t := t + 100	
WRITE(A, t)		125		WRITE(A, t)	
	READ(A, s)			READ(B, t)	
	s := s * 2			t := t + 100	
	WRITE(A, s)	250		WRITE(B, t)	
READ(B, t)					READ(A, s)
t := t + 100					s := s * 2
WRITE(B, t)			125		WRITE(A, s)
	READ(B, s)				READ(B, s)
	s := s * 2				s := s * 2
	WRITE(B, s)		250		WRITE(B, s)

可串行化调度的优点

	脏写	脏读	不可重复读	幻读
可串行化	无	无	无	无

程序员无需考虑事务并发的问题，全由DBMS来解决

可串行化调度的缺点

可串行化调度的并发度低

在某些场景下，并发事务不需要严格隔离

- 一个事务对部分对象的修改可以暴露(expose)给对其他并发事务
- 弱隔离级别(weaker isolation level)可以提高系统的并发度

Concurrency Control
Isolation Levels

隔离级别(Isolation Levels)

SQL-92规定了并发事务的4种隔离级别(isolation level)

- 读未提交(Read Uncommitted)
- 读提交(Read Committed)
- 可重复读(Repeatable Read)
- 可串行化(Serializable)

在不同隔离级别下，一个事务修改过的对象的值对其他并发事务的可见程度不同

可以在事务开始前设置事务的隔离级别

- `SET TRANSACTION ISOLATION LEVEL <isolation-level>;`

读未提交(Read Uncommitted)

未提交事务(uncommitted txn)所做的修改对其他事务可见

Example (Read Uncommitted)

T_1	T_2	A	Variables
		A = 1	
READ(A, t)			t = 1
	READ(A, s)		s = 1
	s := s * 2		s = 2
	WRITE(A, s)	A = 2	
READ(A, x)			x = 2
	COMMIT		
READ(A, y)			y = 2
COMMIT			
READ(A, z)			z = 2

隔离级别(Isolation Levels)

隔离级别	脏读	不可重复读	幻读
READ UNCOMMITTED	可能	可能	可能

读提交(Read Committed)

只有已提交的事务(committed txn)所做的修改才对其他事务可见

Example (Read Committed)

T_1	T_2	A	Variables
		A = 1	
READ(A, t)			t = 1
	READ(A, s)		s = 1
	s := s * 2		s = 2
	WRITE(A, s)	A = 2	
READ(A, x)			x = 1
	COMMIT		
READ(A, y)			y = 2
COMMIT			
READ(A, z)			z = 2

隔离级别(Isolation Levels)

隔离级别	脏读	不可重复读	幻读
READ UNCOMMITTED	可能	可能	可能
READ COMMITTED	无	可能	可能

可重复读(Repeatable Read)

如果一个事务不修改对象X的值，则该事务在任何时候读到的X值都等于事务启动时读到的X值

Example (Repeatable Read)

T_1	T_2	A	Variables
		A = 1	
READ(A, t)			t = 1
	READ(A, s)		s = 1
	s := s * 2		s = 2
	WRITE(A, s)	A = 2	
READ(A, x)			x = 1
	COMMIT		
READ(A, y)			y = 1
COMMIT			
READ(A, z)			z = 2

隔离级别(Isolation Levels)

隔离级别	脏读	不可重复读	幻读
READ UNCOMMITTED	可能	可能	可能
READ COMMITTED	无	可能	可能
REPEATABLE READ	无	无	可能

可串行化(Serializable)

- 无脏读: T reads only the changes made by committed transactions
- 可重复读: No value read or written by T is changed by any other transaction until T is complete
- 无幻读(phantom): If T reads a set of values based on some search condition, this set is not changed by other transactions until T is complete

隔离级别(Isolation Levels)

隔离级别	脏读	不可重复读	幻读
READ UNCOMMITTED	可能	可能	可能
READ COMMITTED	无	可能	可能
REPEATABLE READ	无	无	可能
SERIALIZABLE	无	无	无

演示

```
CREATE TABLE t (
  id INT PRIMARY KEY,
  val INT NOT NULL
);

SET autocommit=OFF;
```

各种DBMS支持的隔离级别

ISOLATION LEVELS (2013)

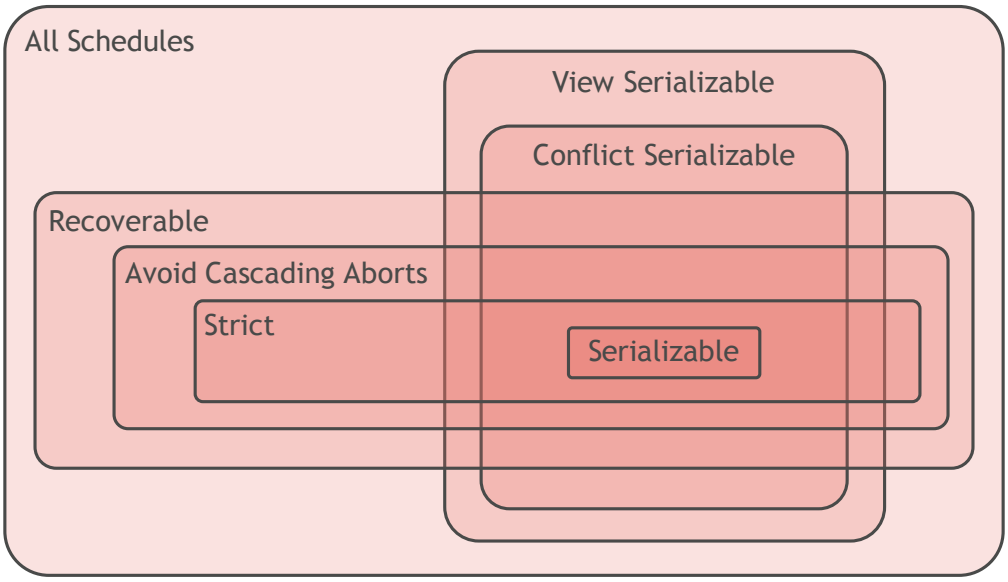
	Default	Maximum
Actian Ingres 10.0/10S	SERIALIZABLE	SERIALIZABLE
Aerospike	READ COMMITTED	READ COMMITTED
Greenplum 4.1	READ COMMITTED	SERIALIZABLE
MySQL 5.6	REPEATABLE READS	SERIALIZABLE
MemSQL 1b	READ COMMITTED	READ COMMITTED
MS SQL Server 2012	READ COMMITTED	SERIALIZABLE
Oracle 11g	READ COMMITTED	SNAPSHOT ISOLATION
Postgres 9.2.2	READ COMMITTED	SERIALIZABLE
SAP HANA	READ COMMITTED	SERIALIZABLE
ScaleDB 1.02	READ COMMITTED	READ COMMITTED
VoltDB	SERIALIZABLE	SERIALIZABLE

Concurrency Control
Serializability

冲突可串行化(Conflict Serializability)

支持可串行化隔离级别的DBMS实施(enforce)的都是冲突可串行化(conflict serializability)

- 冲突可串行化比一般可串行化的条件更严
- 冲突可串行化更便于在DBMS中实施



冲突(Conflicts)

两个操作冲突(conflict)，如果

- 这两个操作属于不同的事务
- 这两个操作涉及相同的对象，且至少一个操作是写

写-写冲突(Write-Write Conflicts, W-W)

写-写冲突可能导致脏写(dirty write)

Example (写-写冲突)

T_1	T_2	A	B
		25	25
READ(A, t)			
t := t + 100			
	READ(A, s)		
	s := s * 2		
	WRITE(A, s)	50	
WRITE(A, t)		125	
	READ(B, s)		
	s := s * 2		
READ(B, t)			
t := t + 100			
WRITE(B, t)			125
	WRITE(B, s)		50

写-读冲突(Write-Read Conflicts, W-R)

写-读冲突可能导致脏读(dirty read)

Example (写-读冲突)

T_1	T_2	A	B
		25	25
READ(A, t)			
t := t + 100			
WRITE(A, t)		125	
	READ(A, s)		
	s := s * 2		
	WRITE(A, s)	250	
	READ(B, s)		
	s := s * 2		
	WRITE(B, s)		50
READ(B, t)			
t := t + 100			
WRITE(B, t)			150

读-写冲突(Read-Write Conflicts, R-W)

读-写冲突可能导致不可重复读(unrepeatable read)

Example (读-写冲突)

T_1	T_2	A
		1
READ(A, t)		
	READ(A, s)	
	s := s - 1	
	WRITE(A, s)	0
READ(A, t)		
t := t - 1		
WRITE(A, t)		-1

事务的简化表示

对DBMS而言，事务中与调度相关的操作只有对象的读和写

Example

T_1	T_2
READ(A, t)	
t := t + 100	
WRITE(A, t)	
	READ(A, s)
	s := s * 2
	WRITE(A, s)
READ(B, t)	
t := t + 100	
WRITE(B, t)	
	READ(B, s)
	s := s * 2
	WRITE(B, s)

$\longrightarrow$

T_1	T_2
r(A)	
w(A)	
	r(A)
	w(A)
r(B)	
w(B)	
	r(B)
	w(B)

冲突等价(Conflict Equivalence)

两个调度冲突等价(conflict equivalent)，如果

- 这两个调度涉及相同事务的相同操作
- 每一对冲突的操作在两个调度中的顺序都相同

Example (冲突等价)

T_1	T_2		T_1	T_2
r(A)			r(A)	
w(A)			w(A)	
	r(A)		r(B)	
	w(A)	$\equiv$	w(B)	
r(B)				r(A)
w(B)				w(A)
	r(B)			r(B)
	w(B)			w(B)

冲突可串行化调度(Conflict Serializable Schedules)

如果一个调度冲突等价于某个串行调度，则该调度是冲突可串行化调度(conflict serializable schedule)

Example (冲突可串行化调度)

T_1	T_2		T_1	T_2
r(A)			r(A)	
w(A)			w(A)	
	r(A)		r(B)	
	w(A)	$\equiv$	w(B)	
r(B)				r(A)
w(B)				w(A)
	r(B)			r(B)
	w(B)			w(B)

冲突可串行化调度(Conflict Serializable Schedules)

Schedule S is conflict serializable if you are able to transform S into a serial schedule by swapping consecutive non-conflicting operations of different transactions

Example (冲突可串行化调度)

T_1	T_2
r(A)	
w(A)	
	r(A)
	w(A)
r(B)	
w(B)	
	r(B)
	w(B)

$\equiv$

T_1	T_2
r(A)	
w(A)	
	r(A)
r(B)	
	w(A)
w(B)	
	r(B)
	w(B)

$\equiv$

T_1	T_2
r(A)	
w(A)	
r(B)	
	r(A)
	w(A)
w(B)	
	r(B)
	w(B)

$\equiv$

T_1	T_2
r(A)	
w(A)	
r(B)	
	r(A)
w(B)	
	w(A)
	r(B)
	w(B)

非冲突可串行化调度

Example (非冲突可串行化调度)

T_1	T_2
r(A)	
	r(A)
	w(A)
w(A)	
r(B)	
w(B)	
	r(B)
	w(B)

$\not\equiv$

T_1	T_2
r(A)	
w(A)	
r(B)	
w(B)	
	r(A)
	w(A)
	r(B)
	w(B)

$\not\equiv$

T_1	T_2
r(A)	
	r(A)
	w(A)
w(A)	
r(B)	
w(B)	
	r(B)
	w(B)

$\not\equiv$

T_1	T_2
	r(A)
	w(A)
	r(B)
	w(B)
r(A)	
w(A)	
r(B)	
w(B)	

冲突可串行化测试(Conflict Serializability Test)

第1步: 将调度S表示为优先图(precedence graph)

- 每个顶点代表S中的一个事务
- 从事务T_i到事务T_j有一条有向边(arc)，如果T_i的某个操作o_i和T_j的某个操作o_j冲突，并且o_i在S中先于o_j

第2步: S是冲突可串行化调度，当且仅当其优先图没有环(acyclic)

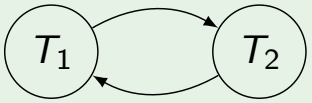
- 优先图顶点的任意拓扑序(topological order)表示了一个与S冲突等价的串行调度

冲突可串行化测试例1

Example (冲突可串行化测试)

T_1	T_2
r(A)	
	r(A)
	w(A)
w(A)	
r(B)	
w(B)	
	r(B)
	w(B)

Precedence Graph



The schedule is not conflict serializable

冲突可串行化测试例2

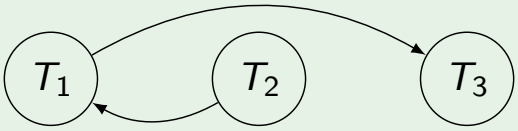
Example (冲突可串行化测试)

T_1	T_2	T_3
r(A)		
w(A)		
		r(A)
		w(A)
	r(B)	
	w(B)	
r(B)		
w(B)		

$\equiv$

T_1	T_2	T_3
	r(B)	
	w(B)	
r(A)		
w(A)		
r(B)		
w(B)		
		r(A)
		w(A)

Precedence Graph

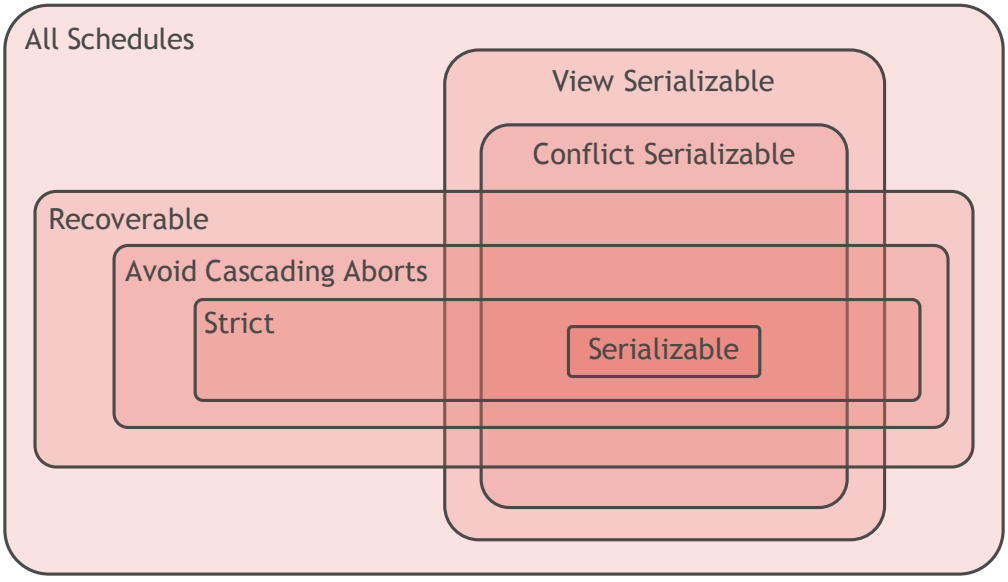


The schedule is conflict serializable

视图可串行化(View Serializability)

视图可串行化(view serializability)是比冲突可串行化更弱的概念

- 测试和实施冲突可串行化很难
- 没有DBMS实施视图可串行化



视图可串行化调度(View Serializable Schedules)

两个调度S_1和S_2视图等价(view equivalent)，如果

- 如果S_1中事务T_1读了对象A的初始值，则S_2中T_1也读了A的初始值
- 如果S_1中事务T_1读了事务T_2修改过的A值，则S_1中T_1也读了T_2修改过的A值
- 如果S_1中事务T_1写了A的最终值，则S_2中T_1也写了A的最终值

如果一个调度视图等价于某个串行调度，则该调度是视图可串行化调度(view serializable schedule)

Example (视图可串行化调度)

T_1	T_2	T_3
r(A)		
	w(A)	
w(A)		
		w(A)

$\equiv_{view}$

T_1	T_2	T_3
r(A)		
w(A)		
	w(A)	
		w(A)

冲突可串行化vs视图可串行化

冲突可串行化调度一定是视图可串行化调度

视图可串行化调度不一定是冲突可串行化调度

- 视图可串行化但非冲突可串行化的调度一定包含盲写(blind write)

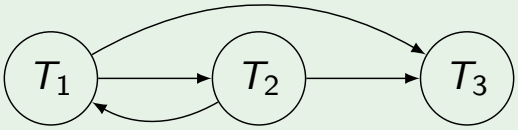
Example

T_1	T_2	T_3
r(A)		
	w(A)	
w(A)		
		w(A)

$\equiv_{view}$

T_1	T_2	T_3
r(A)		
w(A)		
	w(A)	
		w(A)

Precedence Graph



The schedule is view serializable but is not conflict serializable

并发控制协议(Concurrency Control Protocols)

并发控制协议用于对并发事务实施正确的(运行时)调度，而无需预先确定整个(静态)调度

悲观(pessimistic)并发控制协议

- 假定冲突很多
- 不允许任何冲突发生

乐观(optimistic)并发控制协议

- 假定冲突很少
- 冲突发生了，再去解决

并发控制协议(Concurrency Control Protocols)

方法1: 基于锁的并发控制(Lock-based Concurrency Control)

方法2: 时间戳定序的并发控制(Timestamp Ordering Concurrency Control)

方法3: 多版本并发控制(Multi-Version Concurrency Control, MVCC)

Lock-based Concurrency Control

Lock-based Concurrency Control
Locks

锁(Locks)

用锁(lock)来保护数据库对象

- 事务T_i只有获得了对象A的锁，才能操作A
- 如果事务T_i请求了对象A的锁，但并未获得，则T_i开始等待，直至获得A的锁为止
- 如果事务T_i已经获得了对象A的锁，则在T_i完成对A的操作后，T_i必须释放A的锁

使用锁的并发事务执行

- LOCK(A): 请求对A加锁
- UNLOCK(A): 释放A的锁

Example

T_1	T_2	Actions of the Scheduler
LOCK(A)		The lock on A is granted to T_1
r(A)		
	LOCK(A)	
w(A)		
r(A)		
UNLOCK(A)		
	r(A)	
	w(A)	
	UNLOCK(A)	

使用锁的并发事务执行

- LOCK(A): 请求对A加锁
- UNLOCK(A): 释放A的锁

Example

T_1	T_2	Actions of the Scheduler
LOCK(A)		The lock on A is granted to T_1
r(A)		
	LOCK(A)	Denied
w(A)		
r(A)		
UNLOCK(A)		
	r(A)	
	w(A)	
	UNLOCK(A)	

使用锁的并发事务执行

- LOCK(A): 请求对A加锁
- UNLOCK(A): 释放A的锁

Example

T_1	T_2	Actions of the Scheduler
LOCK(A)		The lock on A is granted to T_1
r(A)		
	LOCK(A)	Denied
w(A)		
r(A)		
UNLOCK(A)		The lock on A is released
	r(A)	
	w(A)	
	UNLOCK(A)	

使用锁的并发事务执行

- LOCK(A): 请求对A加锁
- UNLOCK(A): 释放A的锁

Example

T_1	T_2	Actions of the Scheduler
LOCK(A)		The lock on A is granted to T_1
r(A)		
	LOCK(A)	Denied
w(A)		
r(A)		
UNLOCK(A)		The lock on A is released
	r(A)	The lock on A is granted to T_2
	w(A)	
	UNLOCK(A)	

使用锁的并发事务执行

- LOCK(A): 请求对A加锁
- UNLOCK(A): 释放A的锁

Example

T_1	T_2	Actions of the Scheduler
LOCK(A)		The lock on A is granted to T_1
r(A)		
	LOCK(A)	Denied
w(A)		
r(A)		
UNLOCK(A)		The lock on A is released
	r(A)	The lock on A is granted to T_2
	w(A)	
	UNLOCK(A)	The lock on A is released

锁的类型(Lock Types)

共享锁(shared lock)/S锁(S-lock)

- 事务T_i只有获得了对象A的共享锁，才能读A

互斥锁(exclusive lock)/X锁(X-lock)

- 事务T_i只有获得了对象A的互斥锁，才能写A
- T_i获得了A的互斥锁后，亦可读A

锁的相容性(Compatibility)

如果对象A上有事务T_i加的共享锁，则事务T_j还可以对A加共享锁，但不可以对A加互斥锁

- 否则产生读-写冲突

如果对象A上有事务T_i加的互斥锁，则事务T_j对A既不能加共享锁，也不能加互斥锁

- 否则产生写-读冲突或写-写冲突

相容矩阵(Compatibility Matrix)

		请求加锁的类型	
		共享锁	互斥锁
已加锁的类型	共享锁	Yes	No
	互斥锁	No	No

使用共享锁和互斥锁的并发事务执行

- S-LOCK(A): 请求对A加共享锁
- X-LOCK(A): 请求对A加互斥锁

Example

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	X-LOCK(A)	
w(A)		
UNLOCK(A)		
	r(A)	
	w(A)	
S-LOCK(A)		
	UNLOCK(A)	
r(A)		
UNLOCK(A)		

使用共享锁和互斥锁的并发事务执行

- S-LOCK(A): 请求对A加共享锁
- X-LOCK(A): 请求对A加互斥锁

Example

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	X-LOCK(A)	Denied
w(A)		
UNLOCK(A)		
	r(A)	
	w(A)	
S-LOCK(A)		
	UNLOCK(A)	
r(A)		
UNLOCK(A)		

使用共享锁和互斥锁的并发事务执行

- S-LOCK(A): 请求对A加共享锁
- X-LOCK(A): 请求对A加互斥锁

Example

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	X-LOCK(A)	Denied
w(A)		
UNLOCK(A)		The exclusive lock on A is released
	r(A)	
	w(A)	
S-LOCK(A)		
	UNLOCK(A)	
r(A)		
UNLOCK(A)		

使用共享锁和互斥锁的并发事务执行

- S-LOCK(A): 请求对A加共享锁
- X-LOCK(A): 请求对A加互斥锁

Example

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	X-LOCK(A)	Denied
w(A)		
UNLOCK(A)		The exclusive lock on A is released
	r(A)	The exclusive lock on A is granted to T_2
	w(A)	
S-LOCK(A)		
	UNLOCK(A)	
r(A)		
UNLOCK(A)		

使用共享锁和互斥锁的并发事务执行

- S-LOCK(A): 请求对A加共享锁
- X-LOCK(A): 请求对A加互斥锁

Example

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	X-LOCK(A)	Denied
w(A)		
UNLOCK(A)		The exclusive lock on A is released
	r(A)	The exclusive lock on A is granted to T_2
	w(A)	
S-LOCK(A)		Denied
	UNLOCK(A)	
r(A)		
UNLOCK(A)		

使用共享锁和互斥锁的并发事务执行

- S-LOCK(A): 请求对A加共享锁
- X-LOCK(A): 请求对A加互斥锁

Example

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	X-LOCK(A)	Denied
w(A)		
UNLOCK(A)		The exclusive lock on A is released
	r(A)	The exclusive lock on A is granted to T_2
	w(A)	
S-LOCK(A)		Denied
	UNLOCK(A)	The exclusive lock on A is released
r(A)		
UNLOCK(A)		

使用共享锁和互斥锁的并发事务执行

- S-LOCK(A): 请求对A加共享锁
- X-LOCK(A): 请求对A加互斥锁

Example

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	X-LOCK(A)	Denied
w(A)		
UNLOCK(A)		The exclusive lock on A is released
	r(A)	The exclusive lock on A is granted to T_2
	w(A)	
S-LOCK(A)		Denied
	UNLOCK(A)	The exclusive lock on A is released
r(A)		The shared lock on A is granted to T_1
UNLOCK(A)		

使用共享锁和互斥锁的并发事务执行

- S-LOCK(A): 请求对A加共享锁
- X-LOCK(A): 请求对A加互斥锁

Example

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	X-LOCK(A)	Denied
w(A)		
UNLOCK(A)		The exclusive lock on A is released
	r(A)	The exclusive lock on A is granted to T_2
	w(A)	
S-LOCK(A)		Denied
	UNLOCK(A)	The exclusive lock on A is released
r(A)		The shared lock on A is granted to T_1
UNLOCK(A)		The shared lock on A is released

使用共享锁和互斥锁的并发事务执行

- S-LOCK(A): 请求对A加共享锁
- X-LOCK(A): 请求对A加互斥锁

Example

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	X-LOCK(A)	Denied
w(A)		
UNLOCK(A)		The exclusive lock on A is released
	r(A)	The exclusive lock on A is granted to T_2
	w(A)	
S-LOCK(A)		Denied
	UNLOCK(A)	The exclusive lock on A is released
r(A)		The shared lock on A is granted to T_1
UNLOCK(A)		The shared lock on A is released

该调度不是冲突可串行化调度

演示

```
CREATE TABLE t (
  id INT PRIMARY KEY,
  val INT NOT NULL
);

SET autocommit=OFF;
```

Lock-based Concurrency Control
Two-Phase Locking

两阶段锁(Two-Phase Locking, 2PL)

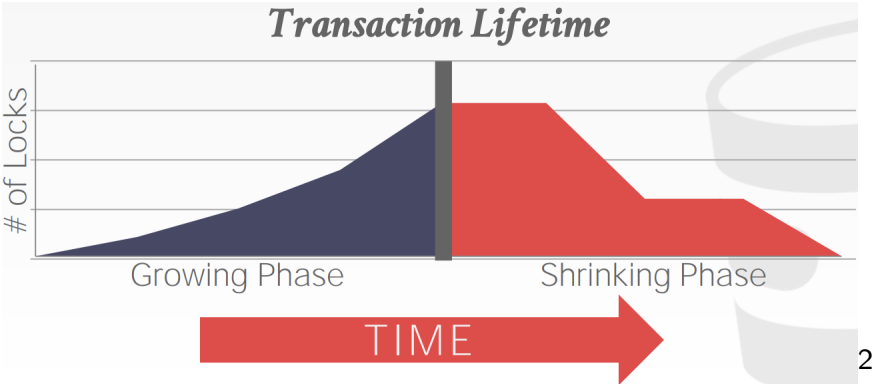
每个事务的执行分为两个阶段

增长阶段(Growing Phase)

- 事务向锁管理器(lock manager)请求需要的锁

萎缩阶段(Shrinking Phase)

- 事务释放它获得的锁，但不能再请求加锁



[2]

[2] 来源: Andy Pavlo, CMU 15-445

两阶段锁(Two-Phase Locking, 2PL)

Example (2PL)

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	X-LOCK(A)	
w(A)		
r(A)		
UNLOCK(A)		
	r(A)	
	w(A)	
	UNLOCK(A)	

两阶段锁(Two-Phase Locking, 2PL)

Example (2PL)

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	X-LOCK(A)	Denied
w(A)		
r(A)		
UNLOCK(A)		
	r(A)	
	w(A)	
	UNLOCK(A)	

两阶段锁(Two-Phase Locking, 2PL)

Example (2PL)

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	X-LOCK(A)	Denied
w(A)		
r(A)		
UNLOCK(A)		The exclusive lock on A is released
	r(A)	
	w(A)	
	UNLOCK(A)	

两阶段锁(Two-Phase Locking, 2PL)

Example (2PL)

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	X-LOCK(A)	Denied
w(A)		
r(A)		
UNLOCK(A)		The exclusive lock on A is released
	r(A)	The exclusive lock on A is granted to T_2
	w(A)	
	UNLOCK(A)	

两阶段锁(Two-Phase Locking, 2PL)

Example (2PL)

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	X-LOCK(A)	Denied
w(A)		
r(A)		
UNLOCK(A)		The exclusive lock on A is released
	r(A)	The exclusive lock on A is granted to T_2
	w(A)	
	UNLOCK(A)	The exclusive lock on A is released

两阶段锁(Two-Phase Locking, 2PL)

Example (2PL)

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	X-LOCK(A)	Denied
w(A)		
r(A)		
UNLOCK(A)		The exclusive lock on A is released
	r(A)	The exclusive lock on A is granted to T_2
	w(A)	
	UNLOCK(A)	The exclusive lock on A is released

该调度是冲突可串行化调度

邹兆年 (CS@HIT) 第10章: 并发控制 2020年春 73 / 142

两阶段锁的性质

优点: 2PL能够保证冲突可串行化

缺点1: 2PL面临着级联中止的问题(cascading abort)

缺点2: 2PL可能导致死锁(deadlock)

Lock-based Concurrency Control
Strict Two-Phase Locking

级联中止(Cascading Aborts)

一个事务中止可能会导致其他事务级联中止(cascading abort)

Example (级联中止)

T_1	T_2
X-LOCK(A)	
X-LOCK(B)	
r(A)	X-LOCK(A)
w(A)	
UNLOCK(A)	
	r(A)
	w(A)
r(B)	
w(B)	
ABORT	
	r(A)

- 2PL允许该调度
- T_1中止时，T_2也要中止，否则T_1修改过的信息将通过T_2泄露给外界

严格调度(Strict Schedules)

A schedule is *strict* if a value written by a txn is not read or overwritten by other txns until that txn finishes

- 严格调度不会引发级联中止

严格两阶段锁(Strict Two-Phase Locking, Strict 2PL)

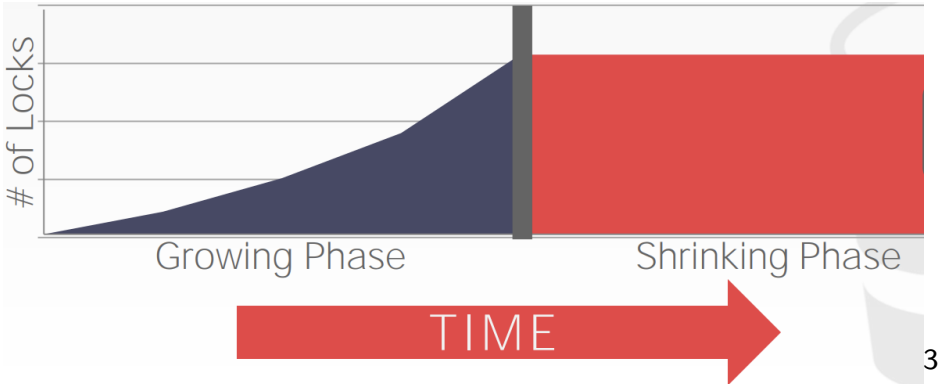
增长阶段(Growing Phase)

- 与2PL的增长阶段相同

萎缩阶段(Shrinking Phase)

- 当事务结束时，释放它获得的全部的锁

严格2PL保证生成严格的冲突可串行化调度，因而不会产生级联中止



[3]

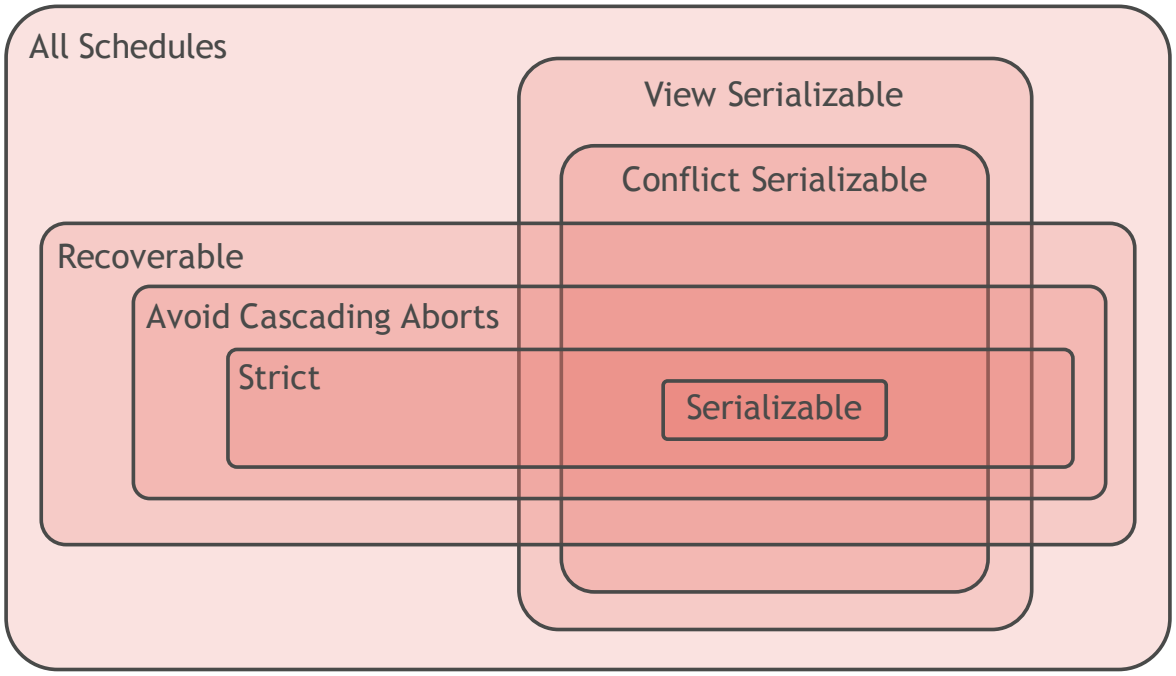
[3] 来源: Andy Pavlo, CMU 15-445

严格2PL

Example (严格2PL)

T_1	T_2
X-LOCK(A)	
X-LOCK(B)	
r(A)	X-LOCK(A)
w(A)	
r(B)	
w(B)	
UNLOCK(A)	
UNLOCK(B)	
ABORT	
	r(A)
	w(A)
	r(A)

调度的类别



Lock-based Concurrency Control
Deadlocks

死锁(Deadlocks)

一组事务形成死锁(deadlock)，如果每个事务都在等待其他事务释放锁

Example (死锁)

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	S-LOCK(B)	
	r(B)	
	S-LOCK(A)	
w(A)		
S-LOCK(B)		
⋮	⋮	

死锁(Deadlocks)

一组事务形成死锁(deadlock)，如果每个事务都在等待其他事务释放锁

Example (死锁)

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	S-LOCK(B)	The shared lock on B is granted to T_2
	r(B)	
	S-LOCK(A)	
w(A)		
S-LOCK(B)		
⋮	⋮	

死锁(Deadlocks)

一组事务形成死锁(deadlock)，如果每个事务都在等待其他事务释放锁

Example (死锁)

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	S-LOCK(B)	The shared lock on B is granted to T_2
	r(B)	
	S-LOCK(A)	Denied!
w(A)		
S-LOCK(B)		
⋮	⋮	

死锁(Deadlocks)

一组事务形成死锁(deadlock)，如果每个事务都在等待其他事务释放锁

Example (死锁)

T_1	T_2	Actions of the Scheduler
X-LOCK(A)		The exclusive lock on A is granted to T_1
r(A)		
	S-LOCK(B)	The shared lock on B is granted to T_2
	r(B)	
	S-LOCK(A)	Denied!
w(A)		
S-LOCK(B)		Denied!
⋮	⋮	

形成死锁(deadlocks)!

死锁的处理

措施1: 死锁检测(Deadlock Detection)

- DBMS检测死锁是否发生
- 如果发生了死锁，则采取办法解除死锁

措施2: 死锁预防(Deadlock Prevention)

- 预防死锁的发生

死锁检测(Deadlock Detection)

方法1: 超时检测(Timeout)

- 如果在给定的时间内没有任何事务执行，则认为死锁发生

方法2: 等待图(waits-for graph)检测

- DBMS用等待图表示事务关于锁的等待关系
- DBMS定期检查等待图中是否存在环(cycle)
- 如果等待图中有环，则死锁发生

等待图(Waits-for Graphs)

等待图(waits-for graph)

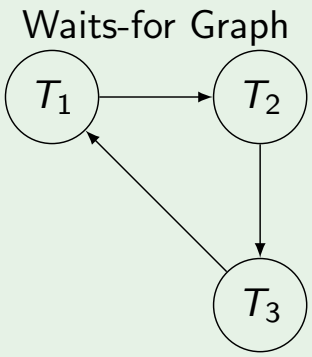
- 顶点代表事务
- 如果事务T_i正在等待事务T_j释放锁，则存在从T_i到T_j的有向边(arc)

事务产生死锁当且仅当等待图中有环(cycle)

Example (等待图)

T_1	T_2	T_3
S-LOCK(A)		
r(A)	X-LOCK(B)	
	w(B)	S-LOCK(C)
S-LOCK(B)		r(C)
(Denied!)	X-LOCK(C)	
	(Denied!)	X-LOCK(A)
		(Denied!)

T_1, T_2, T_3产生死锁

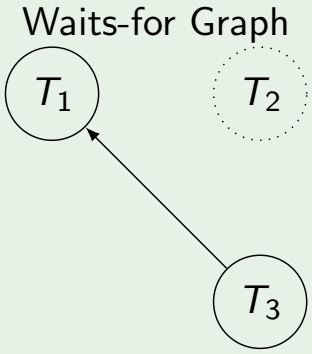


死锁解除(Deadlock Resolution)

从等待图的环(cycle)中选择一个事务作为"牺牲品"，中止该事务

Example (死锁解除)

T_1	T_2	T_3
S-LOCK(A)		
r(A)	X-LOCK(B)	
	w(B)	S-LOCK(C)
S-LOCK(B)		r(C)
(Denied!)	X-LOCK(C)	
	(Denied!)	X-LOCK(A)
		(Denied!)
	ABORT	



死锁解除(Deadlock Resolution)

选择"牺牲品"时需要考虑多种因素

- 事务的年龄/启动时间
- 事务的进度(已执行的查询数量)
- 事务获得的锁的数量
- 需要级联中止的事务数量

还要考虑事务"被牺牲"的次数，防止事务"饿死"(starvation)

死锁预防(Deadlock Prevention)

当事务启动时，DBMS为事务分配一个唯一且固定的优先级(priority)

- 开始得越早，优先级越高

当事务T_i请求事务T_j拥有的锁而无法获得时，DBMS根据T_i和T_j的优先级来裁决如何处理T_1和T_2

死锁预防(Deadlock Prevention)

规则1: Wait-Die ("Old Waits for Young")

- 如果T_i比T_j的优先级高，则T_i等待
- 否则，T_i中止

规则2: Wound-Wait ("Young Waits for Old")

- 如果T_i比T_j的优先级高，则T_j中止
- 否则，T_i等待

事务中止并重启后，其优先级保持不变

死锁预防(Deadlock Prevention)

Example (死锁预防)

T_1	T_2	Wait-Die	Wound-Wait
	X-LOCK(A)		
X-LOCK(A)		T_1 waits	T_2 aborts

T_1	T_2	Wait-Die	Wound-Wait
X-LOCK(A)			
	X-LOCK(A)	T_2 aborts	T_2 waits

Lock-based Concurrency Control
Multi-Granularity Locking

锁的效率问题

锁越多，管理锁的开销越大

- 一个事务访问1亿条元组，就需要加1亿把锁

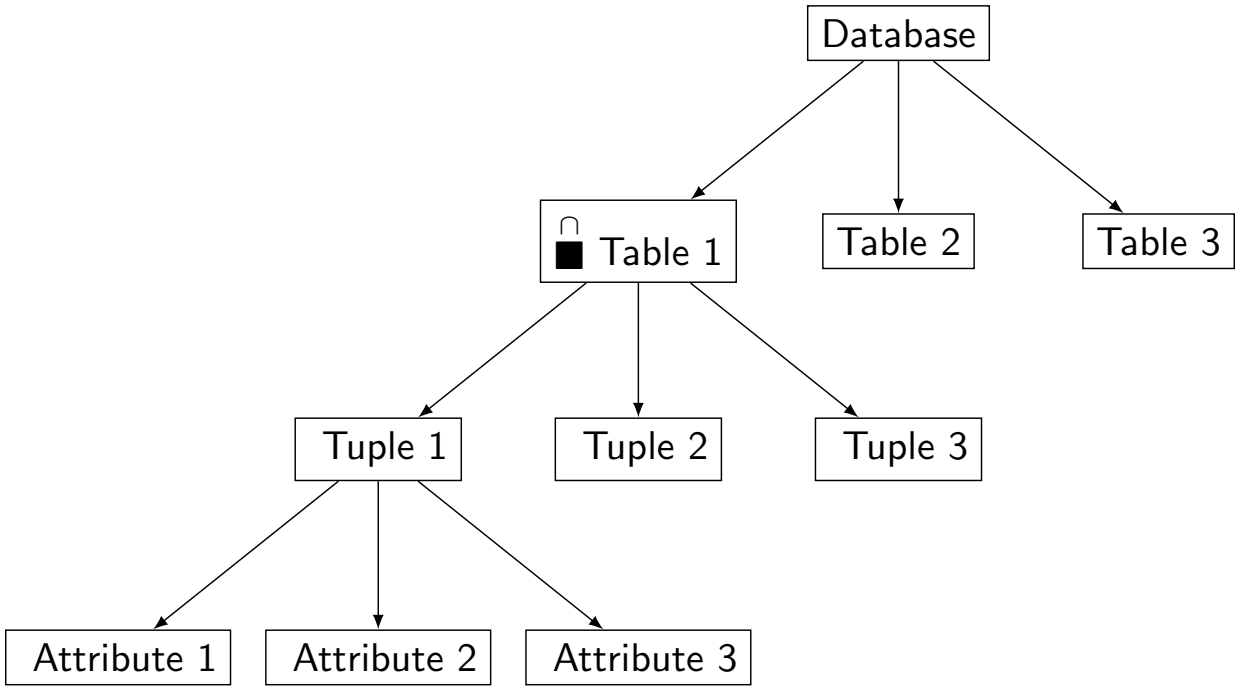
在不合适的粒度上加锁会降低事务并发度

- 一个事务只需访问1条元组，却在整个关系上加锁

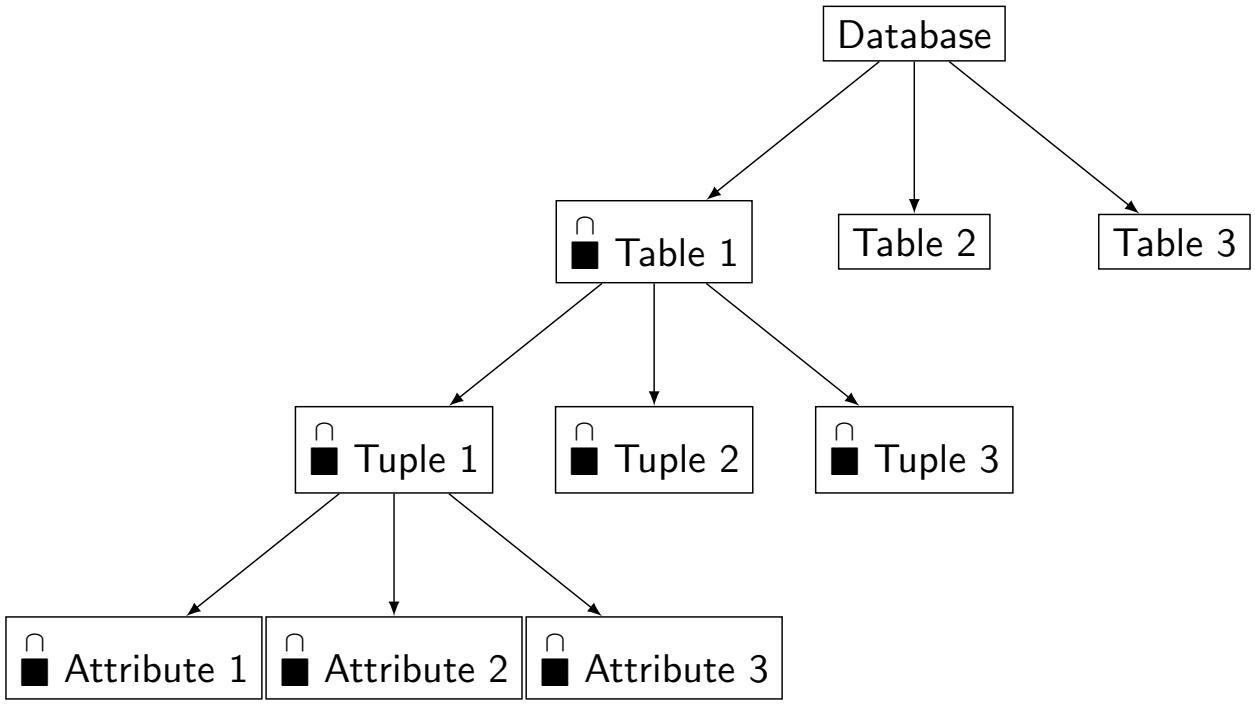
提高锁管理的效率

- 尽可能少加锁
- 在合适的粒度上加锁

锁的粒度(Lock Granularities)



锁的粒度(Lock Granularities)



意向锁(Intension Locks)

IS 意向共享锁(Intension-Shared Locks)/IS锁(IS-Locks)

- 对一个对象加IS锁表示要对该对象的某个(些)后裔加S锁

IX 意向互斥锁(Intension-Exclusive Locks)/IX锁(IX-Locks)

- 对一个对象加IX锁表示要对该对象的某个(些)后裔加X锁或S锁

SIX 共享意向互斥锁(Shared Intension-Exclusive Locks)/SIX锁(SIX-Locks)

- 对一个对象加SIX锁表示要对该对象及其所有后裔加S锁
- 并且对该对象的某个(些)后裔加X锁

相容矩阵(Compatibility Matrix)

		请求锁类型				
		IS	IX	SIX	S	X
拥有锁类型	IS	Yes	Yes	Yes	Yes	No
	IX	Yes	Yes	Yes	No	No
	S	Yes	No	Yes	No	No
	SIX	Yes	No	No	No	No
	X	No	No	No	No	No

多粒度锁协议(Multi-Granularity Locking)

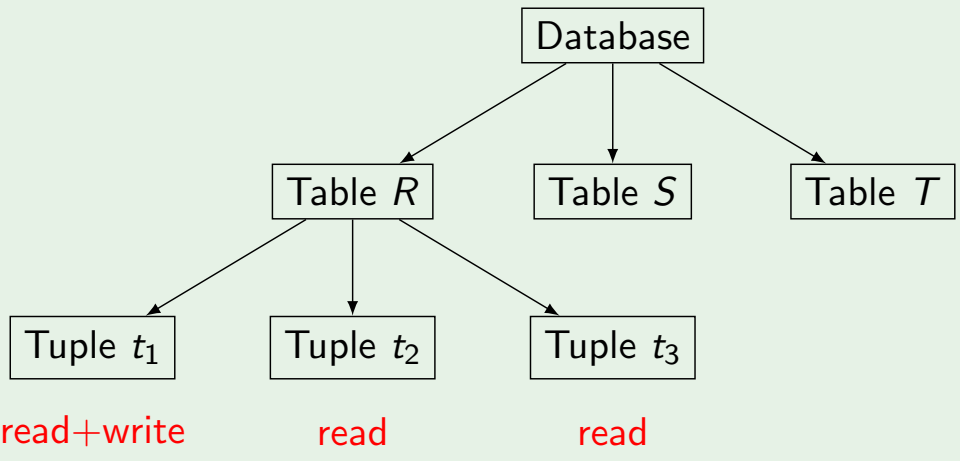
任何事务都要服从下列规则

- 从最高级别对象开始加锁，加锁过程自顶向下
- 对一个对象加IS或S锁之前，必须先获得其父亲对象的IS锁
- 事务对一个对象加IX、SIX或X锁之前，必须先获得其父亲对象的IX锁
- 解锁过程自底向上

多粒度锁协议(Multi-Granularity Locking)

Example (多粒度锁协议)

- 事务T_1扫描关系R并修改元组t_1
- 事务T_2读关系R的元组t_2
- 事务T_3扫描关系R: 对R加S锁被拒，T_3等待



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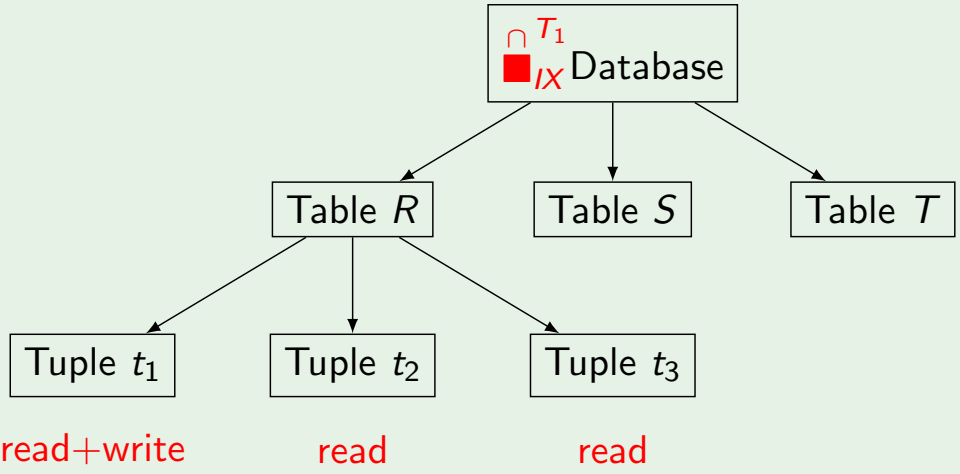

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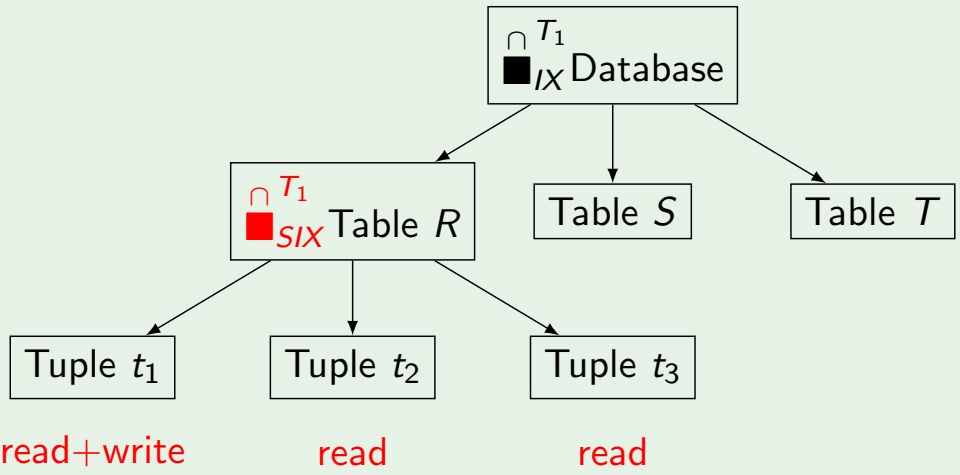

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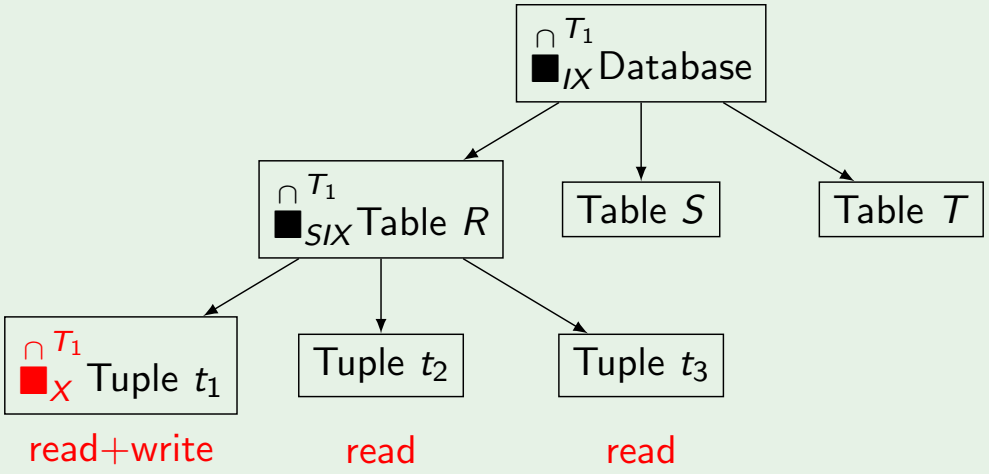

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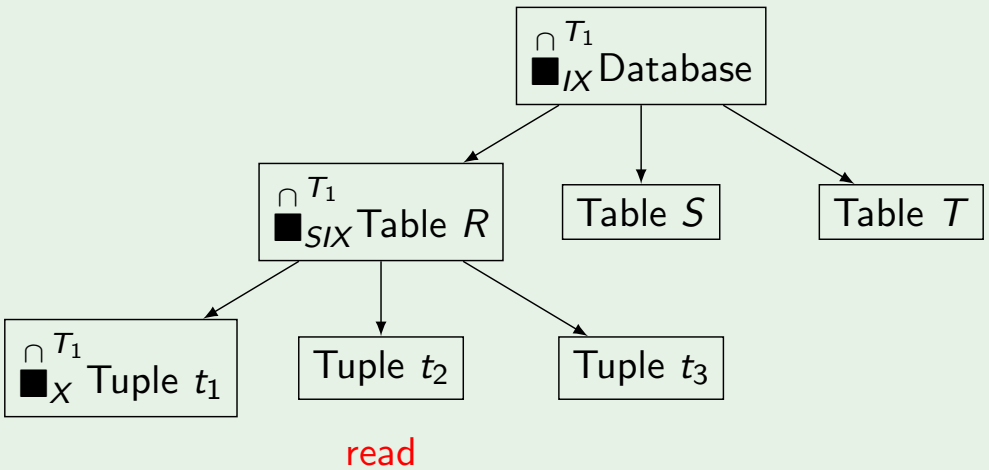

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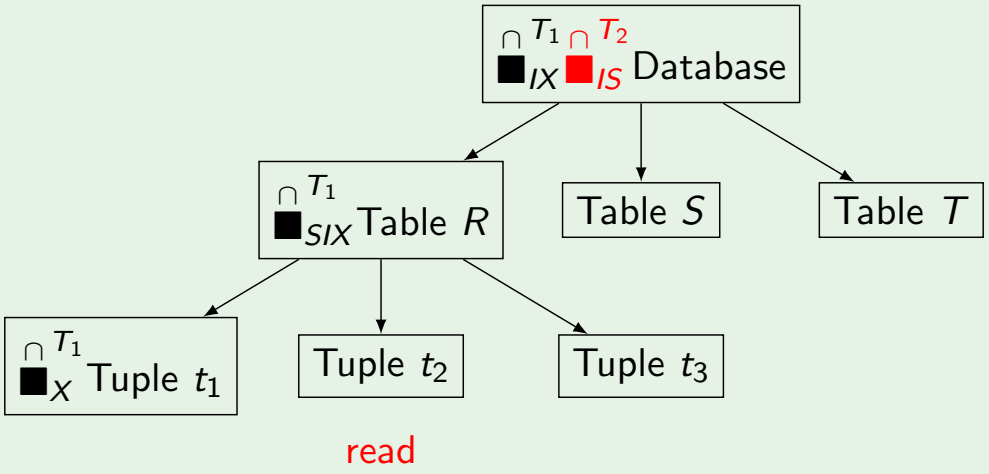

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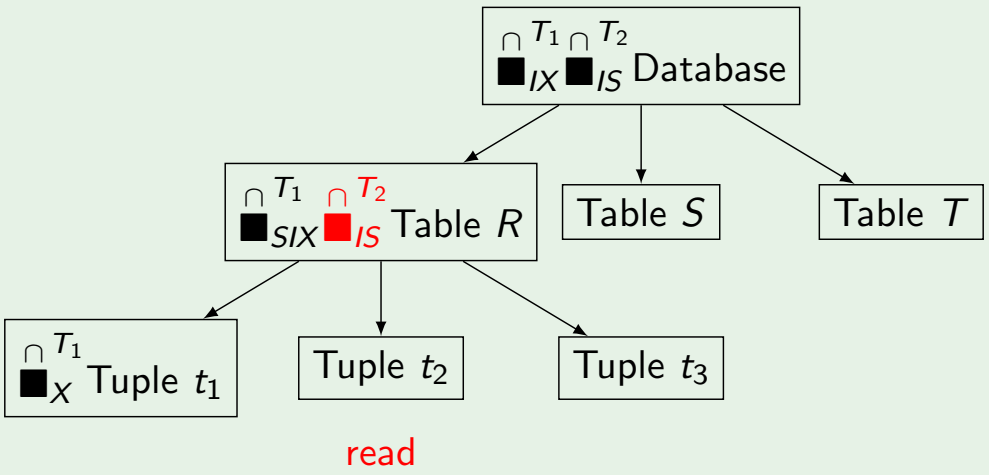

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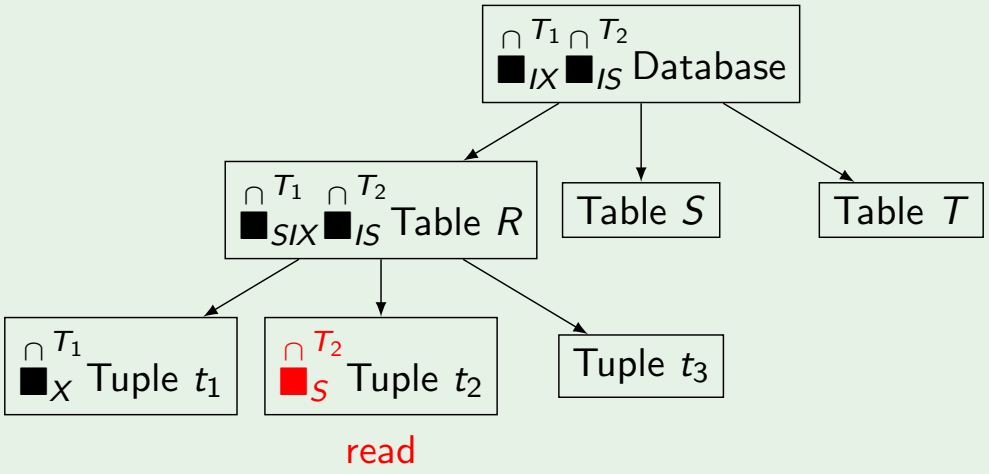

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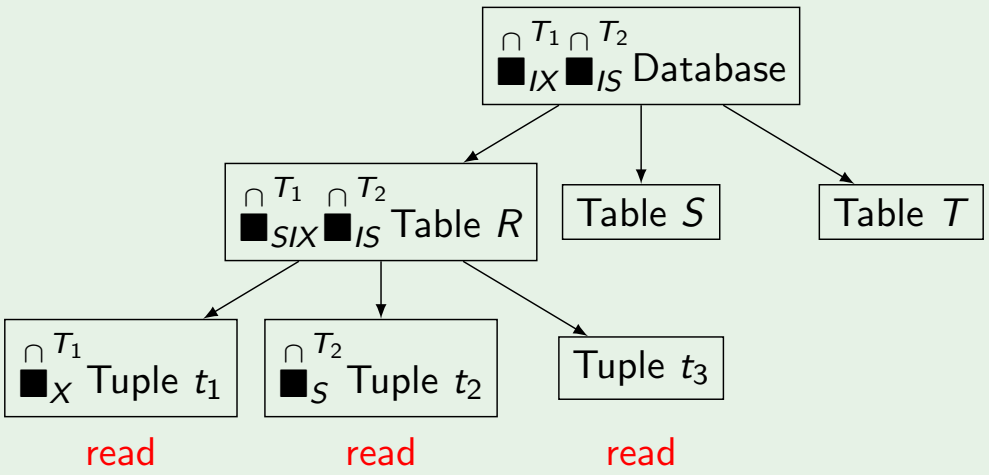

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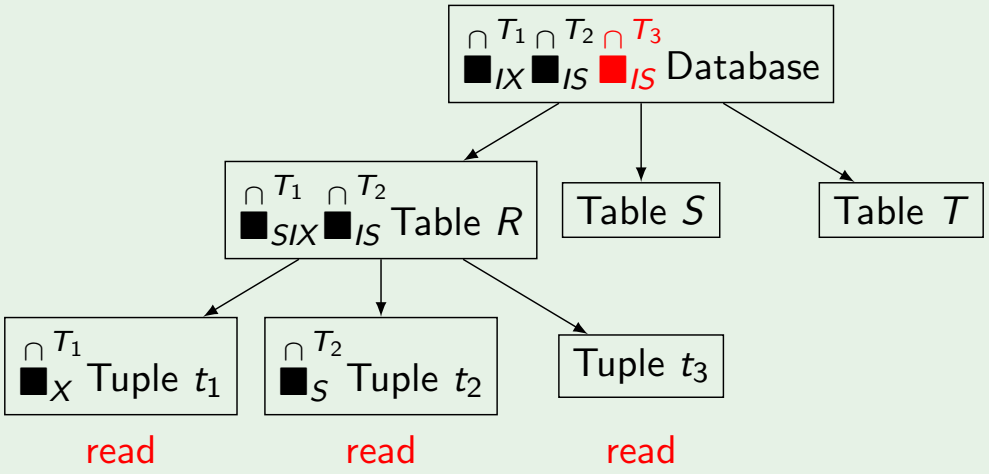


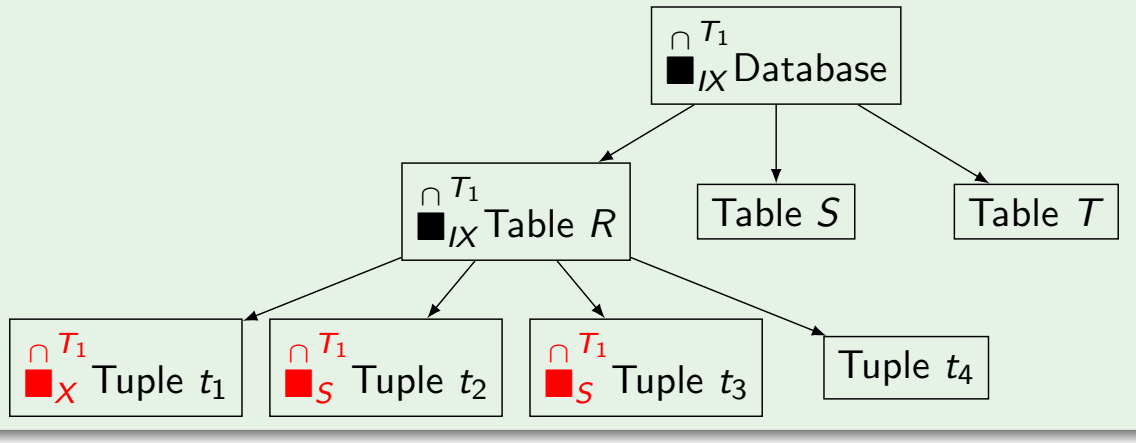
锁升级(Lock Escalation)

如果一个事务已经请求了大量低级别对象上的锁，则DBMS动态地将这些锁升级为上一级别对象上的锁

- 减少锁的数量
- 选择合适的锁粒度

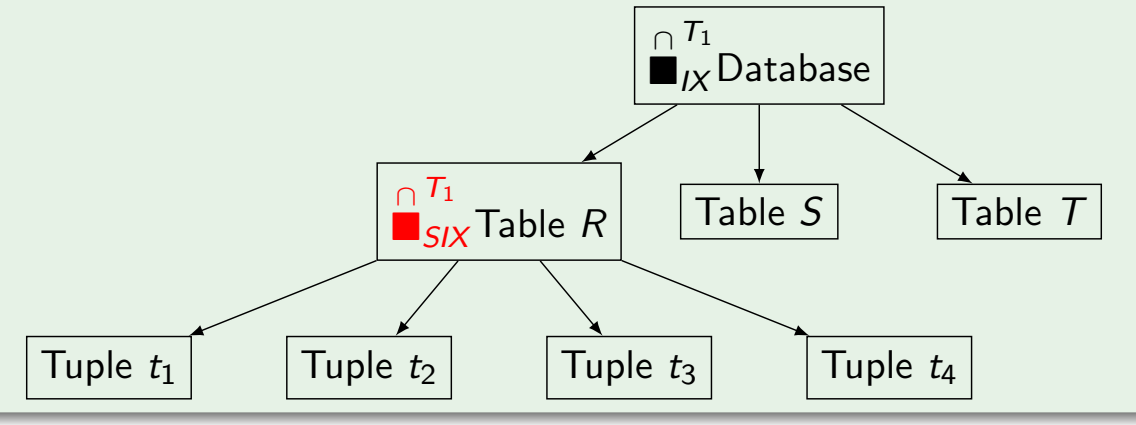
锁升级(Lock Escalation)

Example (锁升级)



锁升级(Lock Escalation)

Example (锁升级)



Lock-based Concurrency Control
Phantoms

动态数据库(Dynamic Databases)

前面假设事务只执行读操作(read)和更新操作(update)

冲突可串行化调度只在固定的数据库上保证

如果事务还执行插入(insert)或删除(delete)操作，则可能出现幻读问题(phantom problem)

幻读(Phantoms)

Example (幻读)

T_1	T_2	T_1 Result
`SELECT MAX(val) FROM t`		200
`WHERE id > 1;`		
	`INSERT INTO t`	t
	`VALUES (3, 300);`	
`SELECT MAX(val) FROM t`		300
`WHERE id > 1;`		

id	val
1	100
2	200

原因: T_1只能锁定t中`id > 1`的元组，无法给不存在的元组加锁

演示

```
CREATE TABLE t (
  id INT PRIMARY KEY,
  val INT NOT NULL
);

SET autocommit=OFF;
```

谓词锁(Predicate Locks)

可以用谓词锁(predicate lock)来解决幻读问题

Example (谓词锁)

T_1	T_2	Lock Actions
`LOCK('id > 1')`		Lock granted to T_1
`SELECT MAX(val) FROM t`		
`WHERE id > 1;`		
	`LOCK('id > 1')`	Denied
`SELECT MAX(val) FROM t`		
`WHERE id > 1;`		
`UNLOCK('id > 1')`		Lock released
`COMMIT`		
	`INSERT INTO t`	Lock granted to T_2
	`VALUES (3, 300);`	
	`UNLOCK('id > 1')`	
	`COMMIT`	

Next-Key锁(Next-Key Locks)

谓词锁的实现代价很高

DBMS实际上经常使用next-key锁(next-key lock)

Timestamp Ordering (T/O) Concurrency Control

时间戳(Timestamp)

DBMS为每个事务T_i分配一个唯一且固定的数，作为T_i的时间戳(timestamp)，记作$TS(T_i)$

- 时间戳单调递增: 分配得越晚，时间戳越大

不同方法分配时间戳的时机不同

- 事务启动时分配，如基本T/O (Basic Timestamp Ordering)
- 事务的验证阶段开始时分配，如乐观并发控制(Optimistic Concurrency Control, OCC)

时间戳定序的并发控制(Timestamp Ordering Concurrency Control, T/O)

事务读写对象前无需加锁

根据时间戳来确定事务的可串行化调度

- 如果$TS(T_i) < TS(T_j)$，则DBMS必须确保在事务的调度所等价的串行调度中，T_i出现在T_j之前

Timestamp Ordering (T/O) Concurrency Control
Basic T/O

Basic T/O

每个对象X关联着2个时间戳

- $RTS(X)$: 成功读X的最晚的事务的时间戳
- $WTS(X)$: 成功写X的最晚的事务的时间戳

对事务的每个读写操作进行时间戳检查

- 如果一个事务准备访问一个"来自未来"的对象，则该事务中止(abort)，并重启(restart)为一个新事务

Basic T/O的读操作

如果$TS(T_i) < WTS(X)$，则

- 中止T_i并重启T_i(分配新的时间戳)

否则

- 允许T_i读X
- 将$RTS(X)$更新为$\max(RTS(X), TS(T_i))$
- 在事务的工作区(workspace)中创建X的局部副本(local copy)，以保证可重复读(repeatable read)

Basic T/O的写操作

如果$TS(T_i) < RTS(X)$或$TS(T_i) < WTS(X)$，则

- 中止并重启T_i

否则

- 允许T_i写X
- 将$WTS(X)$更新为$\max(WTS(X), TS(T_i))$
- 创建X的局部副本

Basic T/O例1

Schedule

T_1 $TS(T_1) = 1$	T_2 $TS(T_2) = 2$
BEGIN	
r(B)	
	BEGIN
	r(B)
	w(B)
r(A)	
	r(A)
	w(A)
COMMIT	COMMIT

Database

Object	RTS	WTS
A	0	0
B	0	0

Basic T/O例1

Schedule

T_1 $TS(T_1) = 1$	T_2 $TS(T_2) = 2$
BEGIN	
r(B)	
	BEGIN
	r(B)
	w(B)
r(A)	
	r(A)
	w(A)
COMMIT	COMMIT

Database

Object	RTS	WTS
A	2	2
B	2	2

没有违反时间戳顺序，T_1和T_2都可以提交

Basic T/O例2

Schedule

T_1 $TS(T_1) = 1$	T_2 $TS(T_2) = 2$
BEGIN	
r(A)	
	BEGIN
	w(A)
	COMMIT
w(A)	
r(A)	
COMMIT	

Database

Object	RTS	WTS
A	0	0
B	0	0

Basic T/O例2

Schedule

T_1 $TS(T_1)=1$	T_2 $TS(T_2)=2$
BEGIN	
r(A)	
	BEGIN
	w(A)
	COMMIT
w(A)	
r(A)	
COMMIT	

Database

Object	RTS	WTS
A	1	2
B	0	0

T_1不能覆盖T_2修改过的A，故T_1中止并重启

Thomas写规则(Thomas Write Rule)

如果$TS(T_i) < RTS(X)$，则

- 中止T_i并重启T_i(分配新的时间戳)

如果$TS(T_i) < WTS(X)$，则

- (Thomas写规则)忽略这个写操作并允许事务继续执行
- 这违反了T_i的时间戳顺序

否则

- 允许T_i写X
- 将$WTS(X)$更新为$\max(WTS(X), TS(T_i))$

Basic T/O例2(续)

Schedule

T_1 $TS(T_1)=1$	T_2 $TS(T_2)=2$
BEGIN	
r(A)	
	BEGIN
	w(A)
	COMMIT
w(A)	
r(A)	
COMMIT	

Database

Object	RTS	WTS
A	1	2
B	0	0

应用Thomas写规则：忽略T_1对A的写操作，继续执行T_1

Basic T/O的性质

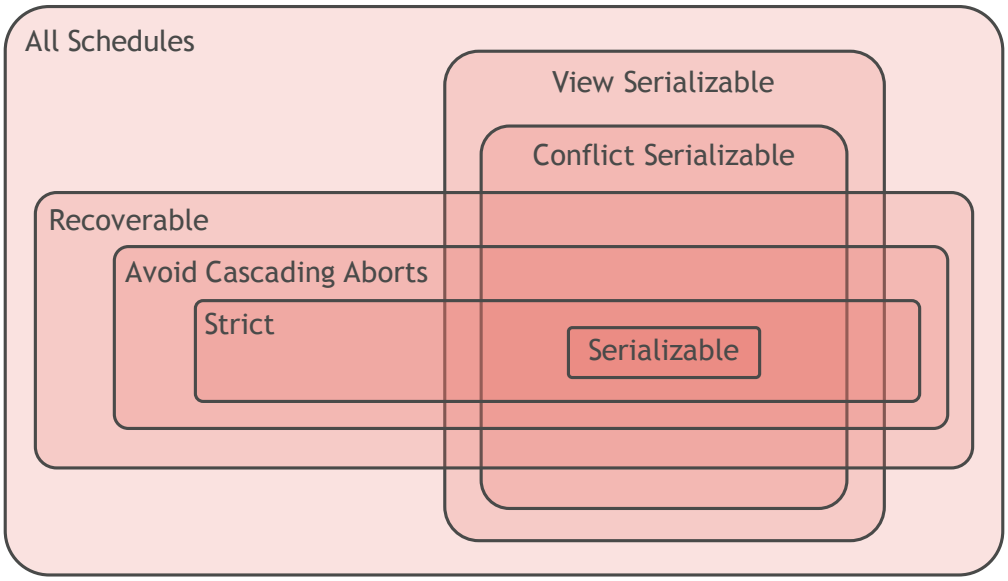
如果不使用Thomas写规则，则Basic T/O生成冲突可串行化调度

- 因为任何事务都无需等待，所以无死锁(deadlock)
- 如果某个长事务(long txn)总是和其他短事务(short txn)发生冲突，则这个长事务可能会“饿死(starve)”(不断中止并重启)

Basic T/O可能生成不可恢复(unrecoverable)的调度

可恢复调度(Recoverable Schedules)

A schedule is *recoverable* if every transaction in that schedule commits only after all the transactions whose changes they read have committed.



可恢复调度(Recoverable Schedules)

Schedule	
T_1 $TS(T_1) = 1$	T_2 $TS(T_2) = 2$
BEGIN w(A)	
	BEGIN r(A) w(B) COMMIT
Crash! COMMIT	

该调度不可恢复

- 故障恢复时，DBMS undo T_1
- 因为T_2读了T_1修改过的A，所以应该undo T_2
- 但T_2已提交，故无法undo T_2

Basic T/O的性能问题

开销大

- 必须将数据复制到事务的局部区(workspace)
- 频繁更新时间戳

长事务可能会饿死

Timestamp Ordering (T/O) Concurrency Control
Optimistic Concurrency Control (OCC)

乐观并发控制(Optimistic Concurrency Control, OCC)

设计目标

- 并发事务的冲突很少
- 大多数事务都很短

事务的三个执行阶段

1. 读阶段(Read Phase)
2. 验证阶段(Validation Phase)
3. 写阶段(Write Phase)

读阶段(Read Phase)

- DBMS为事务创建私有工作区(private workspace)
- 事务读的每个对象都要复制到工作区，以保证可重复读
- 事务对对象的修改写到工作区，而不是数据库
- 将读和写分别记录到读集合(read set)和写集合(write set)中

验证阶段(Validation Phase)

- 当验证阶段开始时，DBMS为事务分配时间戳
- DBMS对事务的写集合(write set)进行检查，判断该事务是否与其他活跃事务(active txn)冲突

写阶段(Write Phase)

- 如果没有冲突，则将写集合(write set)写回数据库
- 否则，中止该事务，并重启为新事务

OCC例1

Schedule

T_1	T_2
BEGIN	BEGIN
//Read	
r(A)	//Read
	r(A)
	//Validate
	//Write
	COMMIT
w(A)	
//Validate	
//Write	
COMMIT	

Database

Object	Value	WTS
A	123	0

OCC例1

Schedule

T_1	T_2
BEGIN	BEGIN
//Read	
r(A)	//Read
	r(A)
	//Validate
	//Write
	COMMIT
w(A)	
//Validate	
//Write	
COMMIT	

Database

Object	Value	WTS
A	123	0

T_1 Workspace

Object	Value	WTS

OCC例1

Schedule

T_1	T_2
BEGIN	BEGIN
//Read	
r(A)	//Read
	r(A)
	//Validate
	//Write
	COMMIT
w(A)	
//Validate	
//Write	
COMMIT	

Database

Object	Value	WTS
A	123	0

T_1 Workspace

Object	Value	WTS
A	123	0

OCC例1

Schedule

T_1	T_2
BEGIN	BEGIN
//Read	
r(A)	//Read
	r(A)
	//Validate
	//Write
	COMMIT
w(A)	
//Validate	
//Write	
COMMIT	

Database

Object	Value	WTS
A	123	0

T_1 Workspace

Object	Value	WTS
A	123	0

T_2 Workspace

Object	Value	WTS

OCC例1

Schedule

T_1	T_2
BEGIN	BEGIN
//Read	
r(A)	//Read
	r(A)
	//Validate
	//Write
	COMMIT
w(A)	
//Validate	
//Write	
COMMIT	

Database

Object	Value	WTS
A	123	0

T_1 Workspace

Object	Value	WTS
A	123	0

T_2 Workspace

Object	Value	WTS
A	123	0

OCC例1

Schedule

T_1	T_2
BEGIN	BEGIN
//Read	
r(A)	//Read
	r(A)
	//Validate
	$TS(T_2) = 1$
	//Write
	COMMIT
w(A)	
//Validate	
//Write	
COMMIT	

Database

Object	Value	WTS
A	123	0

T_1 Workspace

Object	Value	WTS
A	123	0

T_2 Workspace

Object	Value	WTS
A	123	0

OCC例1

Schedule

T_1	T_2
BEGIN	BEGIN
//Read	
r(A)	//Read
	r(A)
	//Validate
	$TS(T_2) = 1$
	//Write
	COMMIT
w(A)	
//Validate	
//Write	
COMMIT	

Database

Object	Value	WTS
A	123	0

T_1 Workspace

Object	Value	WTS
A	123	0

T_2 Workspace

Object	Value	WTS
A	123	0

OCC例1

Schedule

T_1	T_2
BEGIN	BEGIN
//Read	
r(A)	//Read
	r(A)
	//Validate
	$TS(T_2) = 1$
	//Write
	COMMIT
w(A)	
//Validate	
//Write	
COMMIT	

Database

Object	Value	WTS
A	123	0

T_1 Workspace

Object	Value	WTS
A	123	0

OCC例1

Schedule

T_1	T_2
BEGIN	BEGIN
//Read	
r(A)	//Read
	r(A)
	//Validate
	$TS(T_2) = 1$
	//Write
	COMMIT
w(A)	
//Validate	
//Write	
COMMIT	

Database

Object	Value	WTS
A	123	0

T_1 Workspace

Object	Value	WTS
A	456	∞

OCC例1

Schedule

T_1	T_2
BEGIN	BEGIN
//Read	
r(A)	//Read
	r(A)
	//Validate
	$TS(T_2) = 1$
	//Write
	COMMIT
w(A)	
//Validate	
$TS(T_1) = 2$	
//Write	
COMMIT	

Database

Object	Value	WTS
A	123	0

T_1 Workspace

Object	Value	WTS
A	456	∞

OCC例1

Schedule

T_1	T_2
BEGIN	BEGIN
//Read	
r(A)	//Read
	r(A)
	//Validate
	$TS(T_2) = 1$
	//Write
	COMMIT
w(A)	
//Validate	
$TS(T_1) = 2$	
//Write	
COMMIT	

Database

Object	Value	WTS
A	456	2

T_1 Workspace

Object	Value	WTS
A	456	∞

OCC例1

Schedule

T_1	T_2
BEGIN	BEGIN
//Read	
r(A)	//Read
	r(A)
	//Validate
	$TS(T_2) = 1$
	//Write
	COMMIT
w(A)	
//Validate	
$TS(T_1) = 2$	
//Write	
COMMIT	

Database

Object	Value	WTS
A	456	2

验证阶段(Validation Phase)

对任意两个事务T_i和T_j，$TS(T_i) < TS(T_j)$，下面3个条件必须有1个满足:

- 条件1: 在T_j开始前，T_i已完成3个阶段
- 条件2: 在T_j的写阶段开始前，T_i已完成3个阶段，且T_i写的对象均未被T_j读过，即$WS(T_i) \cap RS(T_j) = \emptyset$
- 条件3: 在T_j的读阶段完成前，T_i的读阶段已完成，且T_i写的对象均未被T_j读写过，即$WS(T_i) \cap RS(T_j) = \emptyset$且$WS(T_i) \cap WS(T_j) = \emptyset$

每个条件都保证了T_j的写对T_i不可见

验证条件1

$TS(T_i) < TS(T_j)$; 在T_j开始前，T_i已完成3个阶段

Schedule	
T_1	T_2
BEGIN	
//Read	
//Validate	
//Write	
COMMIT	
	BEGIN
	//Read
	//Validate
	//Write
	COMMIT

该调度就是由时间戳确定的串行调度

验证条件2

$TS(T_i) < TS(T_j)$；在T_j的写阶段开始前，T_i已完成3个阶段，且$WS(T_i) \cap RS(T_j) = \emptyset$

Schedule

T_1	T_2
BEGIN	BEGIN
//Read	
r(A)	
w(A)	//Read
	r(A)
	//Validate
	//Write
	COMMIT
//Validate	
//Write	
COMMIT	

该调度等价于由时间戳确定的串行调度

Schedule

T_1	T_2
BEGIN	BEGIN
//Read	
r(A)	
w(A)	//Read
	r(A)
//Validate	
//Write	
COMMIT	
	//Validate
	//Write
	COMMIT

因为$WS(T_1) \cap RS(T_2) = \{A\}$，所以该调度不等价于由时间戳确定的串行调度

验证条件3

$TS(T_i) < TS(T_j)$；在T_j的读阶段完成前，T_i的读阶段已完成，且$WS(T_i) \cap RS(T_j) = \emptyset$，$WS(T_i) \cap WS(T_j) = \emptyset$

Schedule

T_1	T_2
BEGIN	BEGIN
//Read	
r(A)	
w(A)	//Read
	r(B)
//Validate	
//Write	
COMMIT	
	w(B)
	//Validate
	//Write
	COMMIT

该调度等价于由时间戳确定的串行调度

Schedule

T_1	T_2
BEGIN	BEGIN
//Read	
r(A)	
w(A)	//Read
	r(A)
//Validate	
//Write	
COMMIT	
	r(B)
	//Validate
	//Write
	COMMIT

因为$WS(T_1) \cap RS(T_2) = \{A\}$，所以该调度不等价于由时间戳确定的串行调度

串行验证(Serial Validation)

在临界区(critical section)中内执行事务的验证阶段和写阶段

- 任何时刻只有一个事务处于验证/写阶段
- 当一个事务正在验证时，其他事务不得提交
- 如果一个事务已经完成验证阶段，则只有在其写阶段完成后，其他事务才能开始验证

OCC的特性

在并发事务冲突很少的情况下，OCC很有效

- 事务都是只读的
- 事务访问的数据子集互不相交

OCC的性能问题

- 将数据复制到工作区的开销很大
- 验证阶段和写阶段是瓶颈
- OCC比2PL的事务中止代价高，因为中止事务的读阶段已经完成

Multi-Version Concurrency Control (MVCC)

多版本并发控制(Multi-Version Concurrency Control, MVCC)

DBMS为数据库中每个(逻辑)对象维护多个(物理)版本(version)

- 当事务写一个对象时，DBMS为该对象创建一个新的版本
- 当事务读一个对象时，它读的是该事务启动时已存在的最新的版本

MVCC的特点

写不阻塞读(Writers don't block readers)
读不阻塞写(Readers don't block writers)

只读(read-only)的事务直接在一致性快照(consistent snapshot)上读，无需加锁

MVCC例1

Schedule

T_1	T_2
BEGIN	
r(A)	
	BEGIN
	w(A)
r(A)	
COMMIT	
	COMMIT

Database

Version	Value	Begin	End
A_0	123	0	-

Txn Status Table

TxnId	TS	Status
T_1	1	Active

MVCC例1

Schedule

T_1	T_2
BEGIN	
r(A) A_0	
	BEGIN
	w(A)
r(A)	
COMMIT	
	COMMIT

Database

Version	Value	Begin	End
A_0	123	0	-

Txn Status Table

TxnId	TS	Status
T_1	1	Active

MVCC例1

Schedule

T_1	T_2
BEGIN	
r(A)	
	BEGIN
	w(A)
r(A)	
COMMIT	
	COMMIT

Database

Version	Value	Begin	End
A_0	123	0	-

Txn Status Table

TxnId	TS	Status
T_1	1	Active
T_2	2	Active

MVCC例1

Schedule

T_1	T_2
BEGIN	
r(A)	
	BEGIN
	w(A)
r(A)	
COMMIT	
	COMMIT

Database

Version	Value	Begin	End
A_0	123	0	2
A_1	456	2	-

Txn Status Table

TxnId	TS	Status
T_1	1	Active
T_2	2	Active

MVCC例1

Schedule

T_1	T_2
BEGIN	
r(A)	
	BEGIN
	w(A)
r(A) A_0	
COMMIT	
	COMMIT

Database

Version	Value	Begin	End
A_0	123	0	2
A_1	456	2	-

Txn Status Table

TxnId	TS	Status
T_1	1	Active
T_2	2	Active

MVCC例1

Schedule

T_1	T_2
BEGIN	
r(A)	
	BEGIN
	w(A)
r(A)	
COMMIT	
	COMMIT

Database

Version	Value	Begin	End
A_0	123	0	2
A_1	456	2	-

Txn Status Table

TxnId	TS	Status
T_1	1	Committed
T_2	2	Committed

MVCC例2

Schedule

T_1	T_2
BEGIN	
r(A)	
w(A)	BEGIN
	r(A)
	w(A)
r(A)	
COMMIT	
	COMMIT

Database

Version	Value	Begin	End
A_0	123	0	-

Txn Status Table

TxnId	TS	Status
T_1	1	Active

MVCC例2

Schedule

T_1	T_2
BEGIN	
r(A) A_0	
w(A)	BEGIN
	r(A)
	w(A)
r(A)	
COMMIT	
	COMMIT

Database

Version	Value	Begin	End
A_0	123	0	-

Txn Status Table

TxnId	TS	Status
T_1	1	Active

MVCC例2

Schedule

T_1	T_2
BEGIN	
r(A)	
w(A)	BEGIN
	r(A)
	w(A)
r(A)	
COMMIT	
	COMMIT

Database

Version	Value	Begin	End
A_0	123	0	1
A_1	456	1	-

Txn Status Table

TxnId	TS	Status
T_1	1	Active

MVCC例2

Schedule

T_1	T_2
BEGIN	
r(A)	
w(A)	BEGIN
	r(A)
	w(A)
r(A)	
COMMIT	
	COMMIT

Database

Version	Value	Begin	End
A_0	123	0	1
A_1	456	1	-

Txn Status Table

TxnId	TS	Status
T_1	1	Active
T_2	2	Active

MVCC例2

Schedule

T_1	T_2
BEGIN	
r(A)	
w(A)	BEGIN
	r(A) A_0
	w(A)
r(A)	
COMMIT	
	COMMIT

Database

Version	Value	Begin	End
A_0	123	0	1
A_1	456	1	-

Txn Status Table

TxnId	TS	Status
T_1	1	Active
T_2	2	Active

MVCC例2

Schedule

T_1	T_2
BEGIN	
r(A)	
w(A)	BEGIN
	r(A)
	w(A) Stall
r(A)	
COMMIT	
	COMMIT

Database

Version	Value	Begin	End
A_0	123	0	1
A_1	456	1	-

Txn Status Table

TxnId	TS	Status
T_1	1	Active
T_2	2	Active

MVCC例2

Schedule

T_1	T_2
BEGIN	
r(A)	
w(A)	BEGIN
	r(A)
	w(A)
r(A) A_0	
COMMIT	
	COMMIT

Database

Version	Value	Begin	End
A_0	123	0	1
A_1	456	1	-

Txn Status Table

TxnId	TS	Status
T_1	1	Active
T_2	2	Active

MVCC例2

Schedule

T_1	T_2
BEGIN	
r(A)	
w(A)	BEGIN
	r(A)
	w(A)
r(A)	
COMMIT	
	COMMIT

Database

Version	Value	Begin	End
A_0	123	0	1
A_1	456	1	-

Txn Status Table

TxnId	TS	Status
T_1	1	Committed
T_2	2	Active

MVCC例2

Schedule

T_1	T_2
BEGIN	
r(A)	
w(A)	BEGIN
	r(A)
	w(A)
r(A)	
COMMIT	
	COMMIT

Database

Version	Value	Begin	End
A_0	123	0	1
A_1	456	1	2
A_2	789	2	-

Txn Status Table

TxnId	TS	Status
T_1	1	Committed
T_2	2	Committed

并发控制协议(Concurrency Control Protocol)

写不阻塞读
读不阻塞写
写阻塞写

采用并发控制协议解决写-写冲突问题

- 时间戳定序并发控制(Timestamp Ordering, T/O)
- 乐观并发控制(Optimistic Concurrency Control, OCC)
- 两阶段锁协议(Two-Phase Locking, 2PL)

总结

1. Transactions
2. Concurrency Control
   - Schedules
   - Isolation Levels
   - Serializability
3. Lock-based Concurrency Control
   - Locks
   - Two-Phase Locking
   - Strict Two-Phase Locking
   - Deadlocks
   - Multi-Granularity Locking
   - Phantoms
4. Timestamp Ordering (T/O) Concurrency Control
   - Basic T/O
   - Optimistic Concurrency Control (OCC)
5. Multi-Version Concurrency Control (MVCC)