Introduction to Databases
《数据库引论》

Lecture 12: Transaction Processing
第12讲：事务处理

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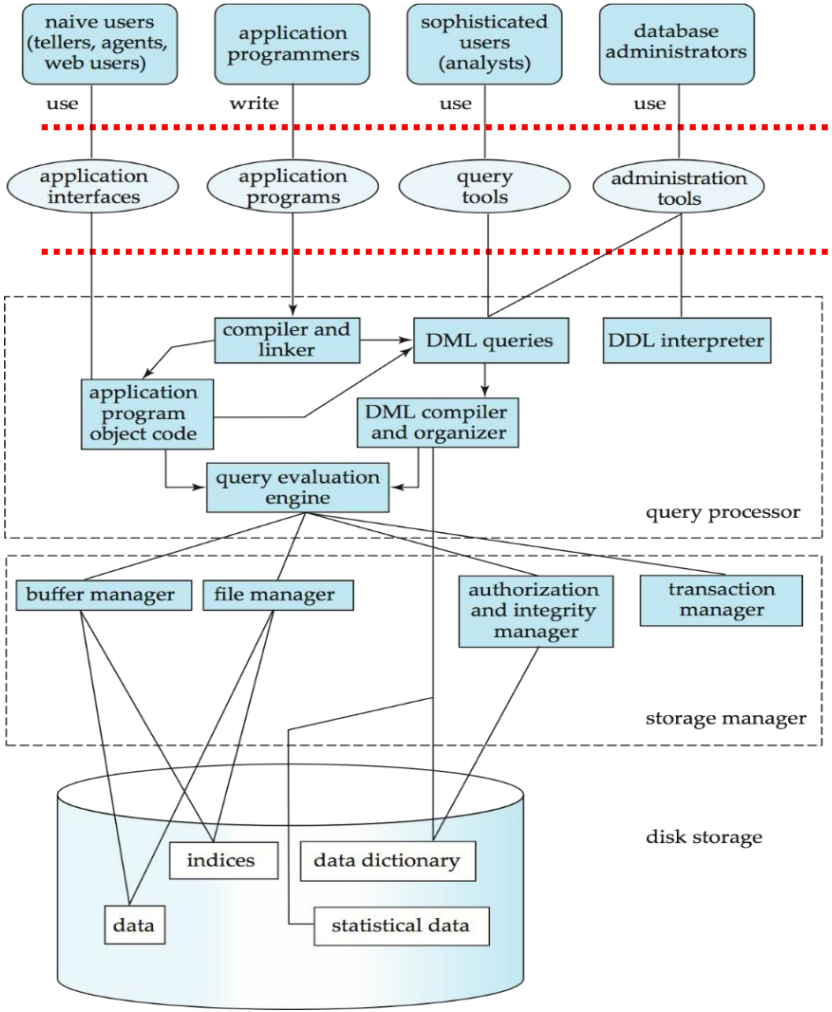
Content of the Course

- **Part 0: Overview**
  - Lect. 0/1 (Feb. 20) - Ch1: Introduction
- **Part 1 Relational Databases**
  - Lect. 2 (Feb. 27) - Ch2: Relational model (data model, relational algebra)
  - Lect. 3 (Mar. 6) - Ch3: SQL (Introduction)
  - Lect. 4 (Mar. 13) – Ch4 & 5: Intermediate & Advanced SQL
- **Part 2 Database Design**
  - Lect. 5 (Mar. 20) - Ch6: Database design based on E-R model
  - Lect. 6 (Mar. 27) - Ch7: Relational database design (Part I)
  - Lect. 7 (Apr. 3) - Ch7: Relational database design (Part II)
- **Midterm exam: Apr. 10**
- **Part 3 Data Storage & Indexing**
  - Lect. 8 (Apr. 17) - Ch12/13: Storage systems & structures
  - Lect. 9 (Apr. 24) - Ch14: Indexing
- **Part 4 Query Processing & Optimization**
  - May 1, holiday, no class
  - Lect. 10 (May 8) - Ch15: Query processing
  - Lect. 11 (May 15) - Ch16: Query optimization
- **Part 5 Transaction Management**
  - Lect. 12 (May 22) - Ch17: Transactions
  - Lect. 13 (May 29) - Ch18: Concurrency control
  - Lect. 14 (Jun. 5) - Ch19: Recovery system
  - Lect. 15 (Jun. 5) – Course review

Final exam: 13:00-15:00, Jun. 18

Database System Structure



Outline

- ☞ **Transaction Concept**
- Schedules
- Serializable Schedule
- Recoverable Schedule
- Testing for Serializability

Transaction Concept

- **A transaction (事务) is a unit of program execution** consisting of multiple operations
  - During transaction execution, the database may be inconsistent
  - After the **transaction is committed**, the database **must be consistent**

- **Two main issues**
  - **Concurrent execution of multiple transactions: concurrency control**
  - **Hardware failures and system crashes: system recovery**

ACID Properties

- **Atomicity（原子性）**
  - Either all operations of the transaction are properly reflected in the database or none are
- **Consistency（一致性）**
  - Execution of a transaction in isolation preserves the consistency of the database
- **Isolation（隔离性）**
  - Although multiple transactions may execute concurrently, each transaction must be unaware of other transactions
- **Durability（持久性）**
  - After a transaction completes successfully, the changes it has made to the database persist, even if there are system failures

Example of Fund Transfer

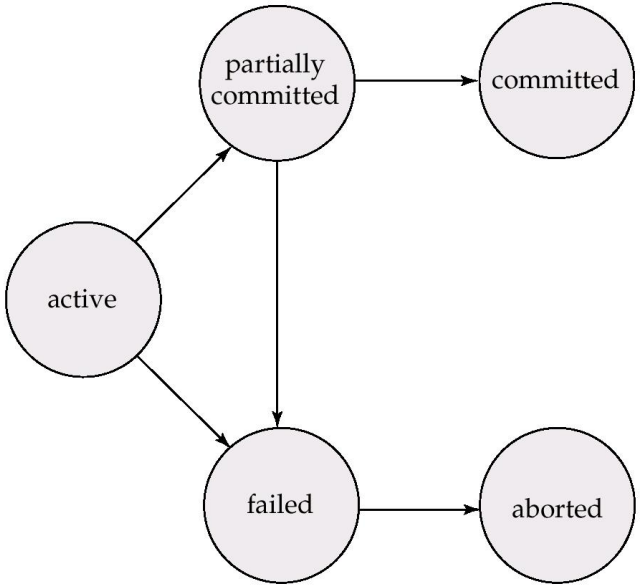
- A transaction to transfer $50 from account A to account B:
  1. read(A)
  2. A := A – 50
  3. write(A)
  4. read(B)
  5. B := B + 50
  6. write(B)
- **Consistency requirement**
  - The sum of A and B is unchanged by the execution of the transaction
- **Atomicity requirement**
  - If the transaction fails after step 3 and before step 6, the system should ensure that its updates are not reflected in the database. Otherwise, an inconsistency will occur

Example of Fund Transfer (Cont.)

- **Durability requirement**
  - Once the user was notified that the transaction has completed, the updates to the database by the transaction must persist despite failures
- **Isolation requirement**
  - If between steps 3 and 6, another transaction is allowed to access the partially updated database, it will see an inconsistent database
  - Can be ensured trivially by running transactions serially, i.e., one after the other. However, executing multiple transactions concurrently has significant benefits

Transaction State

- **Active(活跃)**
  - The initial state. The transaction stays in this state while it is executing
- **Partially committed(部分提交)**
  - After the final statement has been executed
- **Failed(失败)**
  - After discovering that normal execution can no longer proceed
- **Aborted(夭折)**
  - After the transaction has been rolled back （回滚）and the database restored to its state prior to the start of the transaction
  - Restart the transaction – only if no internal logical error happens in the transaction
  - Kill the transaction – problems arising with the transaction, input data, no desirable data found in the database
- **Committed(提交)**
  - After successful completion
- **Terminated(结束)**
  - A transaction is said to have terminated if it has either committed or aborted



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Concurrent Executions

- **Concurrent execution**
  - Multiple transactions are allowed to run concurrently in the system
  - Advantages
    - Increase processor and disk utilization
    - Reduce average response time

- **Concurrency control**
  - Mechanisms to achieve isolation, i.e., to control the interaction among the concurrent transactions in order to prevent them from destroying the consistency of the database

Schedules

- **Schedule（调度）**
  - sequences that indicate the **chronological order** in which instructions of concurrent transactions are executed
  - a schedule for a set of transactions must consist of all instructions of those transactions
  - must preserve the order in which the instructions appear in each individual transaction.
- **Example**
  - Let T_1 transfer **$50** from ***A*** to ***B***, and T_2 transfer **10%** of the balance from ***A*** to ***B***
  - **Schedule 1** is a **serial schedule** (串行调度), in which T_1 is followed by T_2

T_1	T_2
read(A)	
$A := A - 50$	
write (A)	
read(B)	
$B := B + 50$	
write(B)	
	read(A)
	$temp := A * 0.1$
	$A := A - temp$
	write(A)
	read(B)
	$B := B + temp$
	write(B)

Schedule 1

Example Schedule (Cont.)

- Another **serial schedule** where T_2 is followed by T_1

T_1	T_2
read(A)	
$A := A - 50$	
write (A)	
read(B)	
$B := B + 50$	
write(B)	
	read(A)
	$temp := A * 0.1$
	$A := A - temp$
	write(A)
	read(B)
	$B := B + temp$
	write(B)

Schedule 1

T_1	T_2
	read(A)
	$temp := A * 0.1$
	$A := A - temp$
	write(A)
	read(B)
	$B := B + temp$
	write(B)
read(A)	
$A := A - 50$	
write(A)	
read(B)	
$B := B + 50$	
write(B)	

Schedule 2

Example Schedule (Cont.)

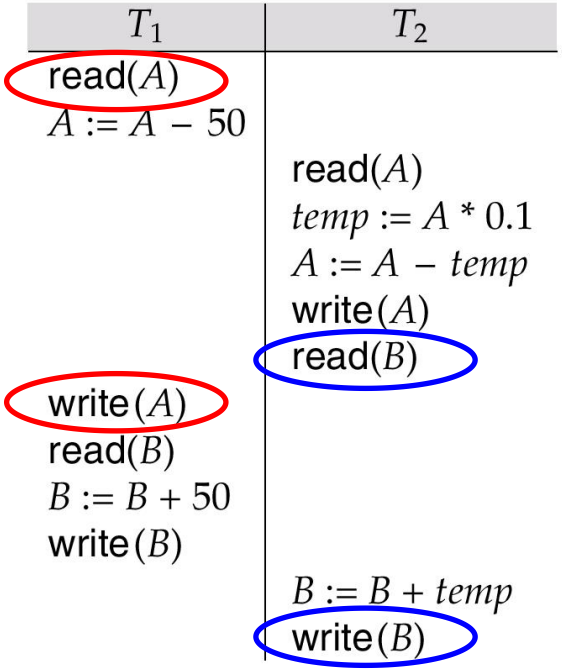
- **Non-serial schedule**
  - Let T_1 and T_2 be the transactions defined previously
  - **Schedule 3** is not a serial schedule, but it is **equivalent to Schedule 1**
    - $A'=(A-50)-(A-50)*0.1=(A-50)*0.9$
    - $B'=B+50+(A-50)*0.1$
    - $A'+B'=A+B$

T_1	T_2
read(A)	
$A := A - 50$	
write(A)	
	read(A)
	$temp := A * 0.1$
	$A := A - temp$
	write(A)
read(B)	
$B := B + 50$	
write(B)	
	read(B)
	$B := B + temp$
	write(B)

Schedule 3

Example Schedule (Cont.)

- The following concurrent schedule does not preserve the value of the sum A + B.
  - A'=A-50
  - B'=B+A*0.1
  - **A'+B' = A+B-50+A*0.1 ≠ A+B**



Schedule 4

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- Transaction Concept
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Serializability（可串行化）

- **Assumption**
  - Each transaction preserves database consistency, thus **serial execution** of a set of transactions preserves database consistency
- **Serializability**
  - **A schedule is serializable if it is equivalent to a serial schedule**
    - **Conflict serializability（冲突可串行性）**
    - **View serializability（视图可串行性）**
- **Note**
  - We ignore operations other than read and write instructions. Our simplified schedules consist of only **read** and **write** instructions

Conflict Serializability

- **Conflict**
  - Given instructions I_i and I_j of transactions T_i and T_j respectively, conflict occurs **iff** there exists some item **Q** accessed by both I_i and I_j, and at least one of these instructions write **Q**
  - **Four cases**
    - I_i = **read(Q)**, I_j = **read(Q)**. I_i **and** I_j **(no conflict)**
    - I_i = **read(Q)**, I_j = **write(Q)**. **(conflict)**
    - I_i = **write(Q)**, I_j = **read(Q)**. **(conflict)**
    - I_i = **write(Q)**, I_j = **write(Q)**. **(conflict)**

- Intuitively, a conflict between I_i and I_j forces a (logical) temporal order between them
- If I_i and I_j are consecutive in a schedule and they do not conflict, their results would remain the same even if they had been interchanged in the schedule

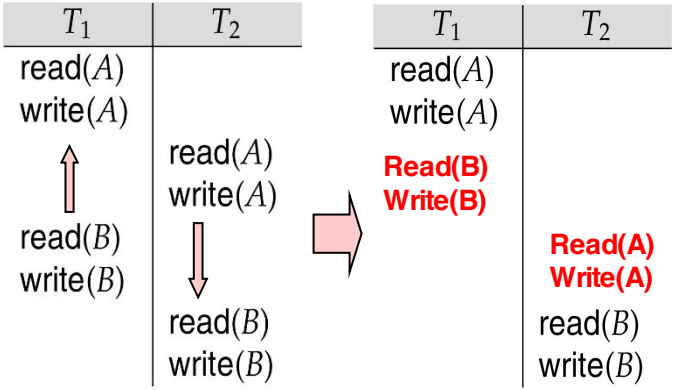
Conflict Serializability (Cont.)

- **Conflict equivalent**
  - If a schedule **S** can be transformed into a schedule **S´** by a series of **swaps of non-conflicting instructions**, we say that **S and S´ are conflict equivalent**
  - We say that a schedule **S is conflict serializable** if it **is conflict equivalent to a serial schedule**
- **Example** of a schedule that is not conflict serializable
  - We are **unable to swap instructions** in the following schedule to obtain either the serial schedule $< T_3, T_4 >$, or the serial schedule $< T_4, T_3 >$.

T_3	T_4
read(**Q**)	
	write(**Q**)
write(**Q**)	

Conflict Serializability (Cont.)

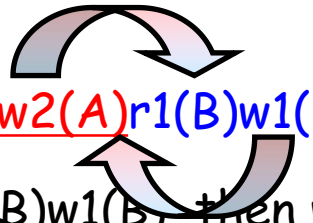
- **Schedule 1** can be transformed into **Schedule 2**, a serial schedule where T_2 follows T_1, by a series of swaps of non-conflicting instructions
- Therefore, **Schedule 1** is **conflict serializable**



Schedule 1 **Schedule 2**

Conflict Serializability (Cont.)

- **Example**



Sc1=r1(A)w1(A)r2(A)w2(A)r1(B)w1(B)r2(B)w2(B)

- Swap w2(A) and r1(B)w1(B), then we have

  r1(A)w1(A)r2(A)r1(B)w1(B)w2(A)r2(B)w2(B)

- Swap r2(A) and r1(B)w1(B), then:

  Sc2 = r1(A)w1(A)r1(B)w1(B)r2(A)w2(A)r2(B)w2(B)

- **Sc2** is equivalent to a serializable schedule T_1, T_2
- Then **Sc1 is conflict serializable**

Conflict Serializability (Cont.)

- A conflict serializable schedule is a serializable schedule, but a serializable schedule is not always conflict serializable.

- E.g., three transactions

  T1=W1(Y)W1(X), T2=W2(Y)W2(X), T3=W3(X)

  - L1=W1(Y)W1(X)W2(Y)W2(X)W3(X) is serializable
  - L2=W1(Y)W2(Y)W2(X)W1(X)W3(X) is not equivalent to L1, and not conflict serializable.
  - L2 is serializable, the result of the schedule is equivalent to L1(final write X is from T3, final write Y is from T2)

View Serializability

- **S and S′ are view equivalent** if the following three conditions are met:
  - For each data item **Q**, if transaction T_i **reads the initial value** of **Q** in schedule **S**, then transaction T_i must, in schedule **S′**, **also read the initial value of Q**.
  - For each data item **Q**, if transaction T_i executes **read(Q)** in schedule **S**, and that value **was produced by transaction** T_j (if any), then transaction T_i must in schedule **S′** also **read the value of Q that was produced by transaction** T_j.
  - For each data item **Q**, **the transaction** (if any) that **performs the final write(Q)** operation in schedule **S** must **perform the final write(Q) operation in schedule S′**

- As can be seen, **view equivalence** is also based purely on **reads** and **writes** alone.

View Serializability (Cont.)

- If a schedule S is view serializable, it is view equivalent to a serial schedule.
- Every conflict serializable schedule is also view serializable.
- A schedule which is view-serializable but not conflict serializable. Equivalent to T_3, T_4, T_6

T_3	T_4	T_6
read(Q)		
	write(Q)	
write(Q)		
		write(Q)

⇔

T_3	T_4	T_6
read(Q)		
Write(Q)		
	Write(Q)	
		write(Q)

- Every view serializable schedule that is not conflict serializable has blind writes - write without read

Other Notions of Serializability

- The following schedule produces the same outcome as the **serial schedule <T_1,T_5>**, yet it is **not conflict equivalent** or **view equivalent**

T_1	T_5
read(A)	
$A := A - 50$	
write(A)	
	read(B)
	$B := B - 10$
	write(B)
read(B)	
$B := B + 50$	
write(B)	
	read(A)
	$A := A + 10$
	write(A)

- Determining such equivalence requires analysis of operations other than read and write.

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Recoverability (可恢复性)

- **Recoverable schedule（可恢复调度）**
  - If a transaction T_j reads a data items previously written by a transaction T_i, the commit operation of T_i appears before the commit operation of T_j
  - The following schedule is **not recoverable** if T_9 commits immediately after the read, because T_9 reads A written by T_8, which should commit before T_9

T_8	T_9
read(A)	
write(A)	
	read(A)
read(B)	

Recoverability (Cont.)

- **Cascading rollback(级联回滚)**
  - A single transaction failure leads to a series of transaction rollbacks
  - Consider the following schedule where none of the transactions has yet committed

T_{10}	T_{11}	T_{12}
read(A)		
read(B)		
write(A)		
	read(A)	
	write(A)	
		read(A)

  - If T_{10} fails, T_{11} and T_{12} must also be rolled back
- **Can lead to the undoing of a significant amount of work**

Recoverability (Cont.)

- **Cascadeless schedules (无级联回滚调度)**
  - For each pair of transactions T_i and T_j such that T_j reads a data item previously written by T_i, the commit operation of T_i appears before the read operation of T_j
  - Cascading rollbacks cannot occur and **every cascadeless schedule is also recoverable**
  - It is **desirable to restrict** the schedules to those that are **cascadeless**

Transaction Definition in SQL

- DML must include a construct for specifying the set of actions that comprise a transaction
- In SQL, a transaction begins implicitly
- A transaction in SQL ends by:
  - **Commit** work: commits current transaction and begins a new one.
  - **Rollback** work: causes current transaction to abort
- Levels of **isolation** specified by SQL-92
  - **Serializable – default**：保证可串行化调度
  - **Repeatable read**：只允许读取已提交数据，两次读取之间数据不能更新
  - **Read committed**：只允许读取已提交数据，不要求可重复读
  - **Read uncommitted**：允许读取未提交数据

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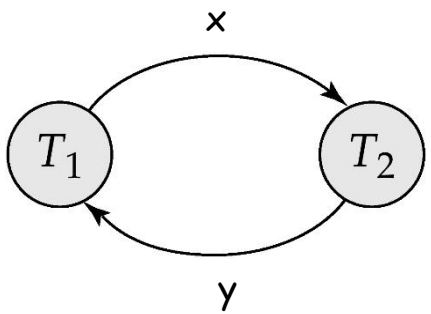
- ☞ **Testing for Serializability**

Testing for Serializability

- Given a set of transactions T_1, T_2, ..., T_n
- **Precedence graph（优先图）**
  - A **direct graph** where the **vertices** are the transactions
  - We draw an **arc** from T_i to T_j if the two transactions **conflict**, and T_i accessed the data item on which the conflict arose earlier
  - We label the arc by the data item that was accessed
- **Example**

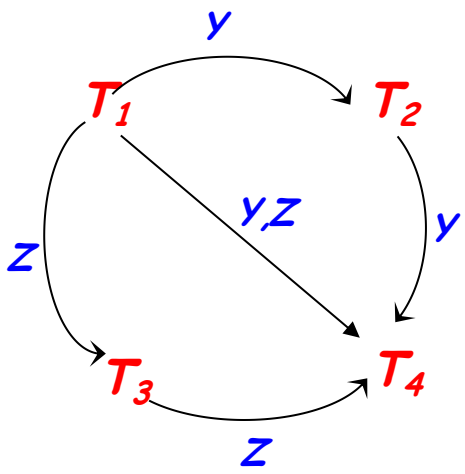


T1 write(x) before T2 read(x)
T1 write(x) before T2 write(x)
T1 read(x) before T2 write(x)

T2 write(y) before T1 read(y)
T2 write(y) before T1 write(y)
T2 read(y) before T1 write(y)

Example Schedule A

T_1	T_2	T_3	T_4	T_5
	read(X)			
read(Y)				
read(Z)				
				read(V)
				read(W)
				read(W)
	read(Y)			
	write(Y)			
		write(Z)		
read(U)				
			read(Y)	
			write(Y)	
			read(Z)	
			write(Z)	
read(U)				
write(U)				



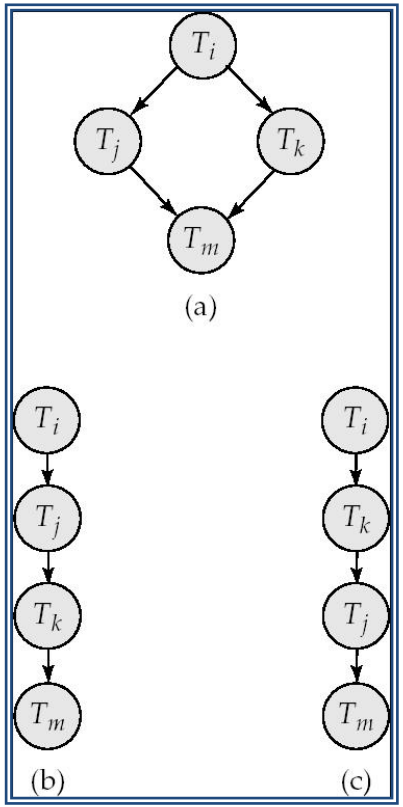
$T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow T_4 \rightarrow T_5$

$T_1 \rightarrow T_3 \rightarrow T_2 \rightarrow T_4 \rightarrow T_5$

……???

Test for Conflict Serializability

- A schedule is **conflict serializable if and only if** its **precedence graph** is **acyclic（无环）**
- If precedence graph is acyclic, the serializability order can be obtained by a **topological sorting of the graph**.
  - For example, a serializability order for Schedule *A* in last slide would be $T_5 \rightarrow T_1 \rightarrow T_3 \rightarrow T_2 \rightarrow T_4$
    - Any others?



Test for View Serializability

- The precedence graph test for conflict serializability must be modified to apply to a test for view serializability

- The problem of checking if a schedule is view serializable falls in the **class of *NP*-complete problems**.
  - Thus existence of an efficient algorithm is unlikely
  - However practical algorithms that just check some *sufficient conditions* for view serializability can still be used

Concurrency Control vs. Serializability Tests

- Testing a schedule for serializability after it has executed is too late
- **Goal** – to develop **concurrency control protocols** that will **assure serializability**.
  - They will generally not examine the precedence graph as it is being created
  - Instead **a protocol** will impose a discipline that avoids non-seralizable schedules
- Tests for serializability help understand why a concurrency control protocol is correct

Assignments

- Practice Exercises: 17.6
- Exercises: 17.15

- Submission DDL: 12:59pm, May 28, 2025

End of Lecture 12