# CS216: Data-Intensive Computing Systems

## **Concurrency Control**

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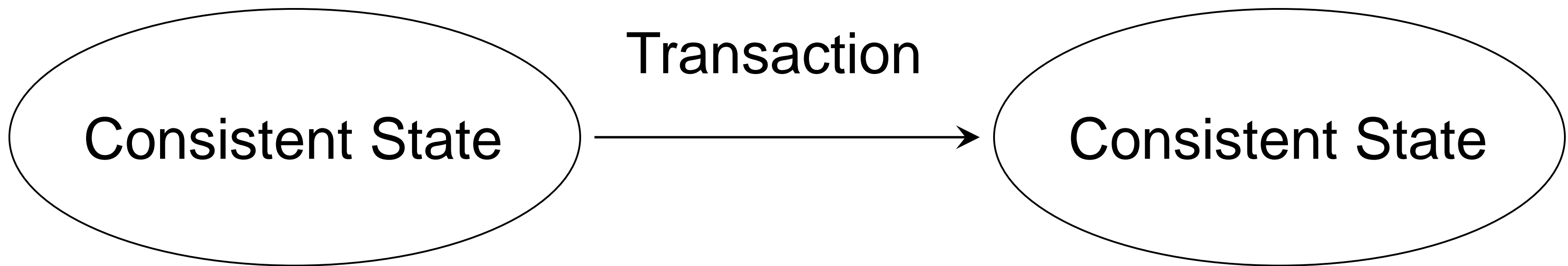
# Transaction

- Programming abstraction
- Implement real-world transactions
  - Banking transaction
  - Airline reservation

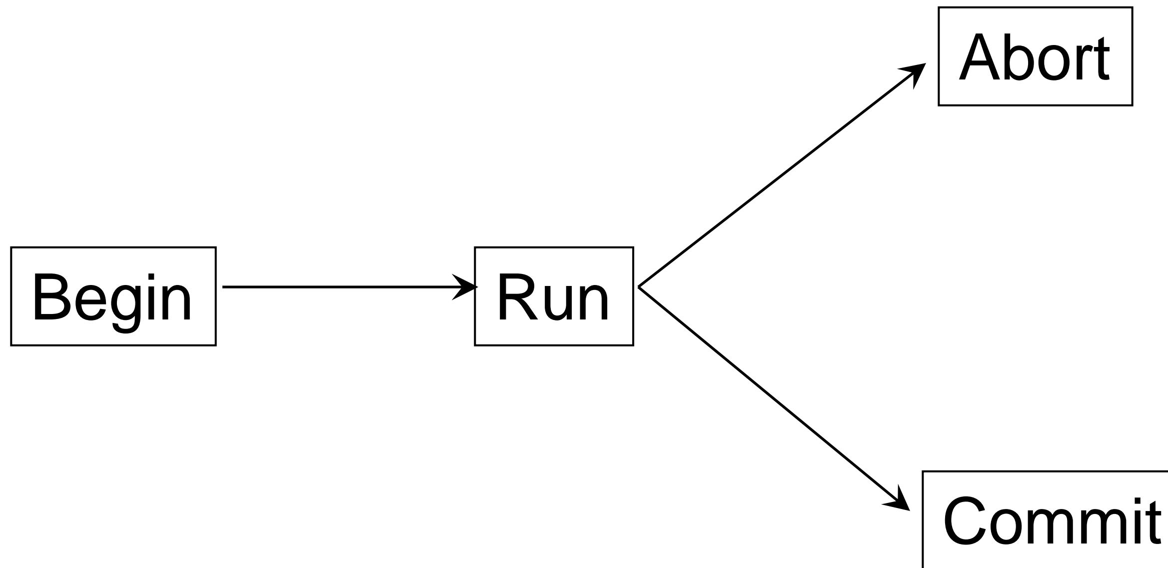
# Transaction: Programmer's Role



# Transaction: System's Role

- Atomicity
  - All changes of the transaction recorded or none at all
- Durability
  - All future transactions see the changes made by this transaction if it completes
- Isolation
  - Net effect as if the transaction executed in isolation

# Transaction: States



# Transactions

- Historical note:
  - Turing Award for Transaction concept
  - Jim Gray (1998)
- Interesting reading:

Transaction Concept: Virtues and Limitations
by Jim Gray

http://www.hpl.hp.com/techreports/tandem/TR-81.3.pdf

# Transaction: Programmer's View

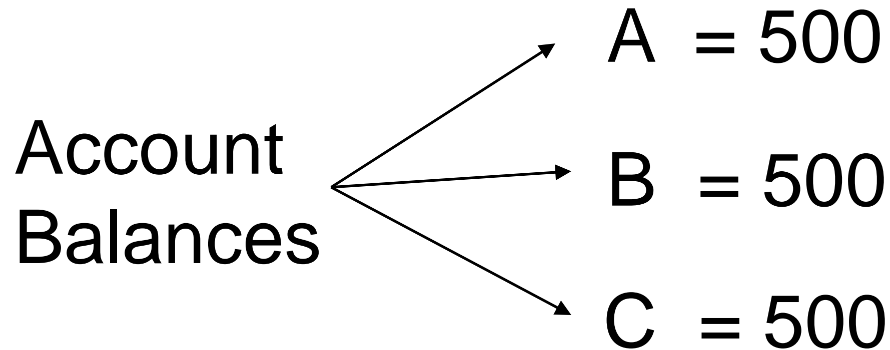
See Section 8.6 of the textbook

# Context

- We have seen:
  - Ensure atomicity in presence of failures
- Next:
  - Ensure Isolation during concurrency

# Issues with Concurrency: Example

Bank database: 3 Accounts

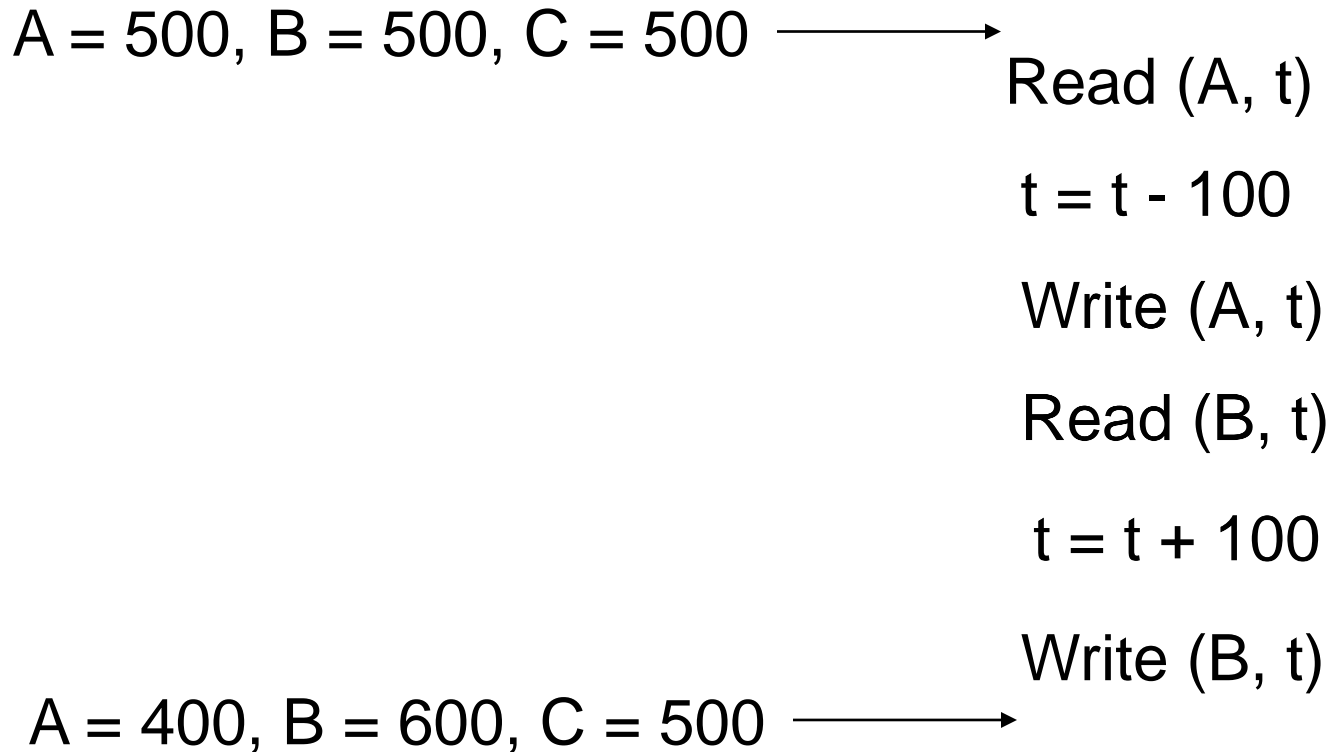



Property: A + B + C = 1500

Money does not leave the system

# Issues with Concurrency: Example

Transaction T1: Transfer 100 from A to B



# Issues with Concurrency: Example

Transaction T2: Transfer 100 from A to C

Read (A, s)

s = s - 100

Write (A, s)

Read (C, s)

s = s + 100

Write (C, s)

| Transaction T1 | Transaction T2 | A | B | C |
| --- | --- | --- | --- | --- |
| | | 500 | 500 | 500 |
| Read (A, t) | | | | |
| t = t - 100 | | | | |
| | Read (A, s) | | | |
| | s = s - 100 | | | |
| | Write (A, s) | 400 | 500 | 500 |
| Write (A, t) | | 400 | 500 | 500 |
| Read (B, t) | | | | |
| t = t + 100 | | | | |
| Write (B, t) | | 400 | 600 | 500 |
| | Read (C, s) | | | |
| | s = s + 100 | | | |
| | Write (C, s) | 400 | 600 | 600 |

400 + 600 + 600 = 1600

| Transaction T1 | Transaction T2 | A | B | C |
|---|---|---|---|---|
| | | 500 | 500 | 500 |
| Read (A, t) | | | | |
| t = t - 100 | | | | |
| Write (A, t) | | 400 | 500 | 500 |
| | Read (A, s) | | | |
| | s = s - 100 | | | |
| | Write (A, s) | 300 | 500 | 500 |
| Read (B, t) | | | | |
| t = t + 100 | | | | |
| Write (B, t) | | 300 | 600 | 500 |
| | Read (C, s) | | | |
| | s = s + 100 | | | |
| | Write (C, s) | 300 | 600 | 600 |

300 + 600 + 600 = 1500

# Terminology

- Schedule:
  - The exact sequence of (relevant) actions of one or more transactions

# Problems

- Which schedules are “correct”?
  - Mathematical characterization

- How to build a system that allows only “correct” schedules?
  - Efficient procedure to enforce correctness

# Correct Schedules: Serializability

- Initial database state is consistent
- Transaction:
  - consistent state $\rightarrow$ consistent state
- Serial execution of transactions:
  - Initial state $\rightarrow$ consistent state
- Serializable schedule:
  - A schedule equivalent to a serial schedule
  - Always "correct"

# Serial Schedule

| | T1 | T2 | A | B | C |
|---|---|---|---|---|---|
| | Read (A, t) | | 500 | 500 | 500 |
| | t = t - 100 | | | | |
| T1 | Write (A, t) | | | | |
| | Read (B, t) | | | | |
| | t = t + 100 | | | | |
| | Write (B, t) | | 400 | 600 | 500 |
| | | Read (A, s) | | | |
| | | s = s - 100 | | | |
| | | Write (A, s) | | | |
| T2 | | Read (C, s) | | | |
| | | s = s + 100 | | | |
| | | Write (C, s) | 300 | 600 | 600 |

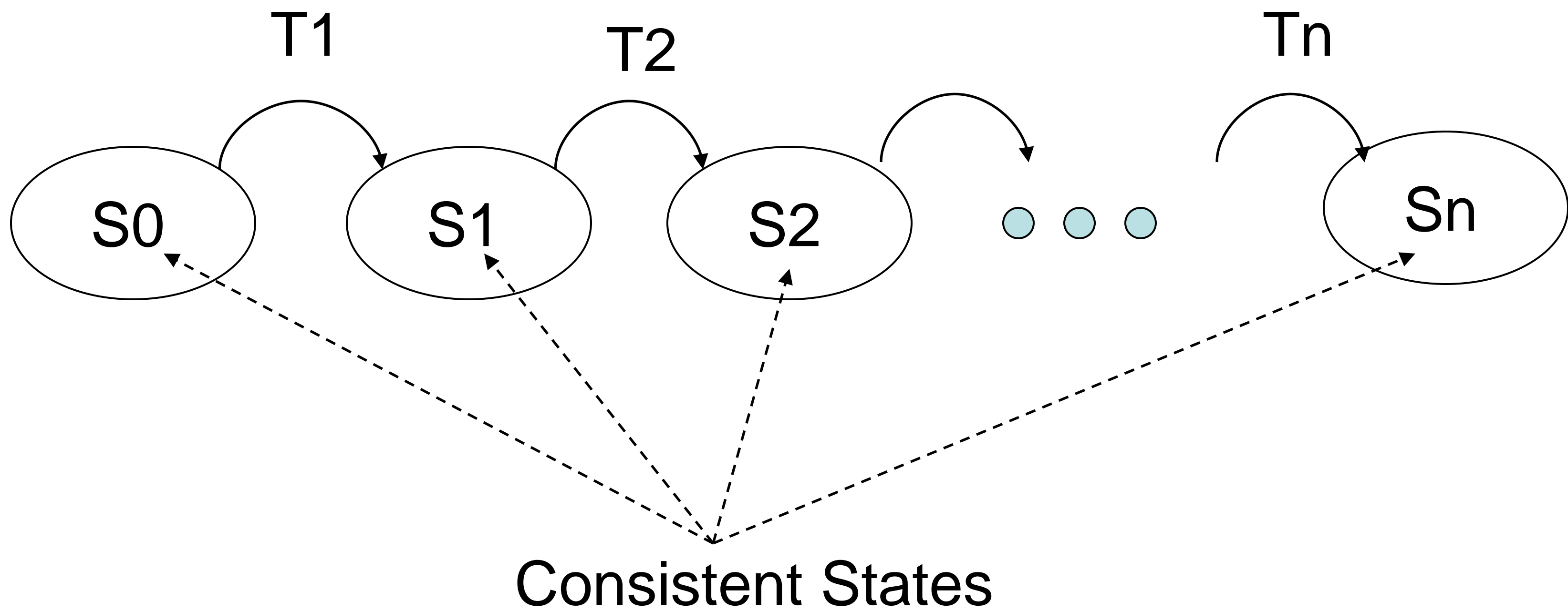
300 + 600 + 600 = 1500

# Serial Schedule

| | T1 | T2 | A | B | C |
|---|---|---|---|---|---|
| | | Read (A, s) | 500 | 500 | 500 |
| | | s = s - 100 | | | |
| T2 | | Write (A, s) | | | |
| | | Read (C, s) | | | |
| | | s = s + 100 | | | |
| | | Write (C, s) | 400 | 500 | 600 |
| | Read (A, t) | | | | |
| | t = t - 100 | | | | |
| | Write (A, t) | | | | |
| T1 | Read (B, t) | | | | |
| | t = t + 100 | | | | |
| | Write (B, t) | | 300 | 600 | 600 |

300 + 600 + 600 = 1500

# Serial Schedule



# Is this Serializable?

| Transaction T1 | Transaction T2 |
|---|---|
| Read (A, t) | |
| t = t - 100 | |
| Write (A, t) | |
| | Read (A, s) |
| | s = s - 100 |
| | Write (A, s) |
| Read (B, t) | |
| t = t + 100 | |
| Write (B, t) | |
| | Read (C, s) |
| | s = s + 100 |
| | Write (C, s) |

# Equivalent Serial Schedule

| Transaction T1 | Transaction T2 |
| --- | --- |
| Read (A, t) | |
| t = t - 100 | |
| Write (A, t) | |
| Read (B, t) | |
| t = t + 100 | |
| Write (B, t) | |
| | Read (A, s) |
| | s = s - 100 |
| | Write (A, s) |
| | Read (C, s) |
| | s = s + 100 |
| | Write (C, s) |

# Is this Serializable?

| Transaction T1 | Transaction T2 |
|---|---|
| Read (A, t) | |
| t = t - 100 | |
| | Read (A, s) |
| | s = s - 100 |
| | Write (A, s) |
| Write (A, t) | |
| Read (B, t) | |
| t = t + 100 | |
| Write (B, t) | |
| | Read (C, s) |
| | s = s + 100 |
| | Write (C, s) |

No. In fact, it leads to inconsistent state

# Is this Serializable?

| Transaction T1 | Transaction T2 |
|---|---|
| Read (A, t) | |
| t = t - 100 | |
| | Read (A, s) |
| | s = s - ~~100~~ 0 |
| | Write (A, s) |
| Write (A, t) | |
| Read (B, t) | |
| t = t + 100 | |
| Write (B, t) | |
| | Read (C, s) |
| | s = s + ~~100~~ 0 |
| | Write (C, s) |

# Is this Serializable?

| Transaction T1 | Transaction T2 |
| --- | --- |
| Read (A, t) | |
| t = t - 100 | |
| | Read (A, s) |
| | s = s - 0 |
| | Write (A, s) |
| Write (A, t) | |
| Read (B, t) | |
| t = t + 100 | |
| Write (B, t) | |
| | Read (C, s) |
| | s = s + 0 |
| | Write (C, s) |

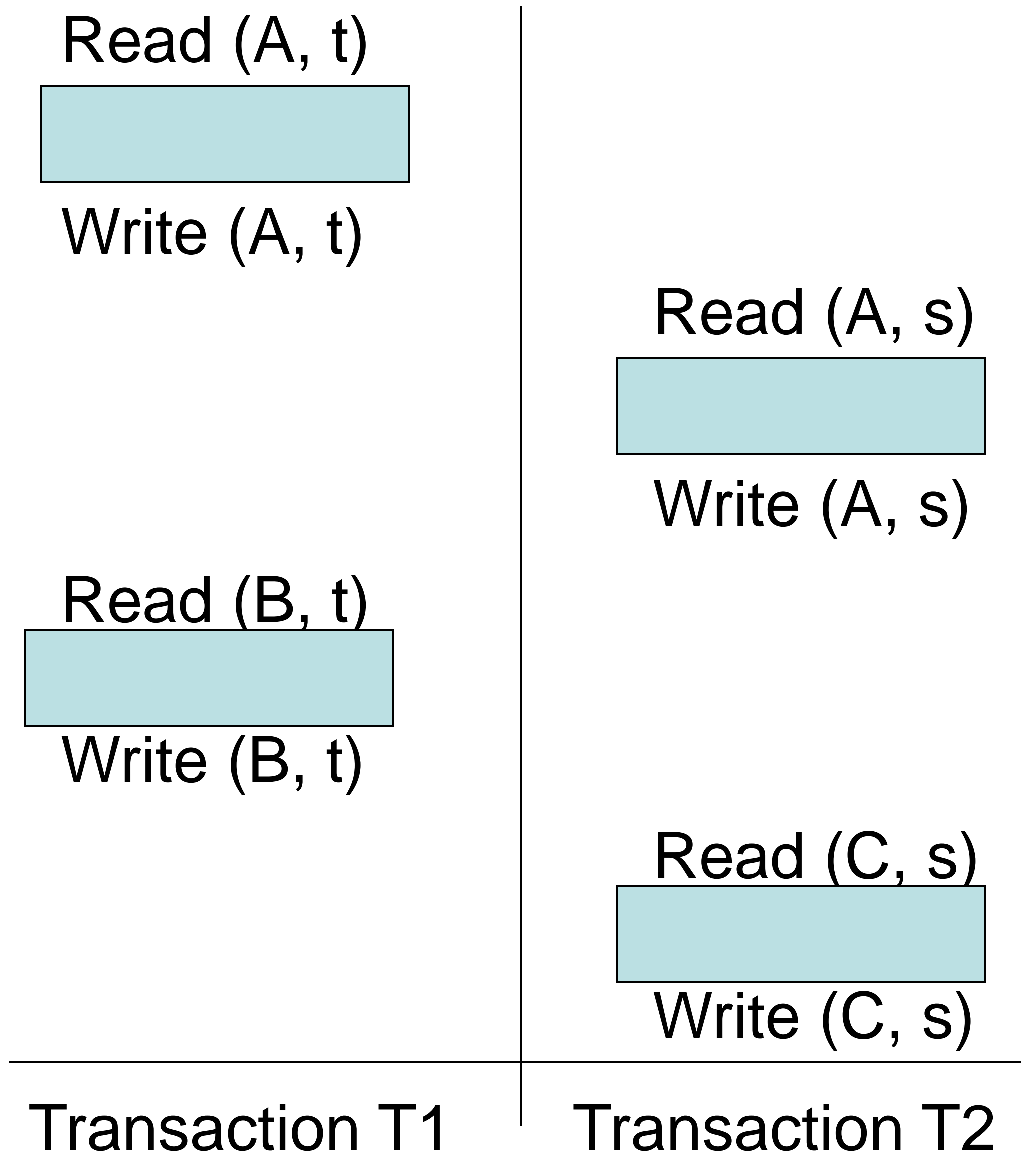
Yes, T2 is no-op

# Serializable Schedule

| Transaction T1 | Transaction T2 |
| --- | --- |
| Read (A, t) | |
| t = t - 100 | |
| | Read (A, s) |
| | s = s - 0 |
| | Write (A, s) |
| Write (A, t) | |
| Read (B, t) | |
| t = t + 100 | |
| Write (B, t) | |
| | Read (C, s) |
| | s = s + 0 |
| | Write (C, s) |

Serializability depends on code details

# Serializable Schedule




Still Serializable!

# Serializability

- General Serializability:
  - Hard to determine
- Goal: weaker serializability
  - Determined from database operations alone
- Database Operations:
  - Reads, Writes, Inserts, …

# Simpler Notation

$r_T(X)$ Transaction T reads X

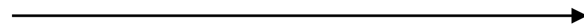
$w_T(X)$ Transaction T writes X

# What is X in r (X)?

- X could be any component of a database:
  - Attribute of a tuple
  - Tuple
  - Block in which a tuple resides
  - A relation
  - …

# New Notation: Example Schedule

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

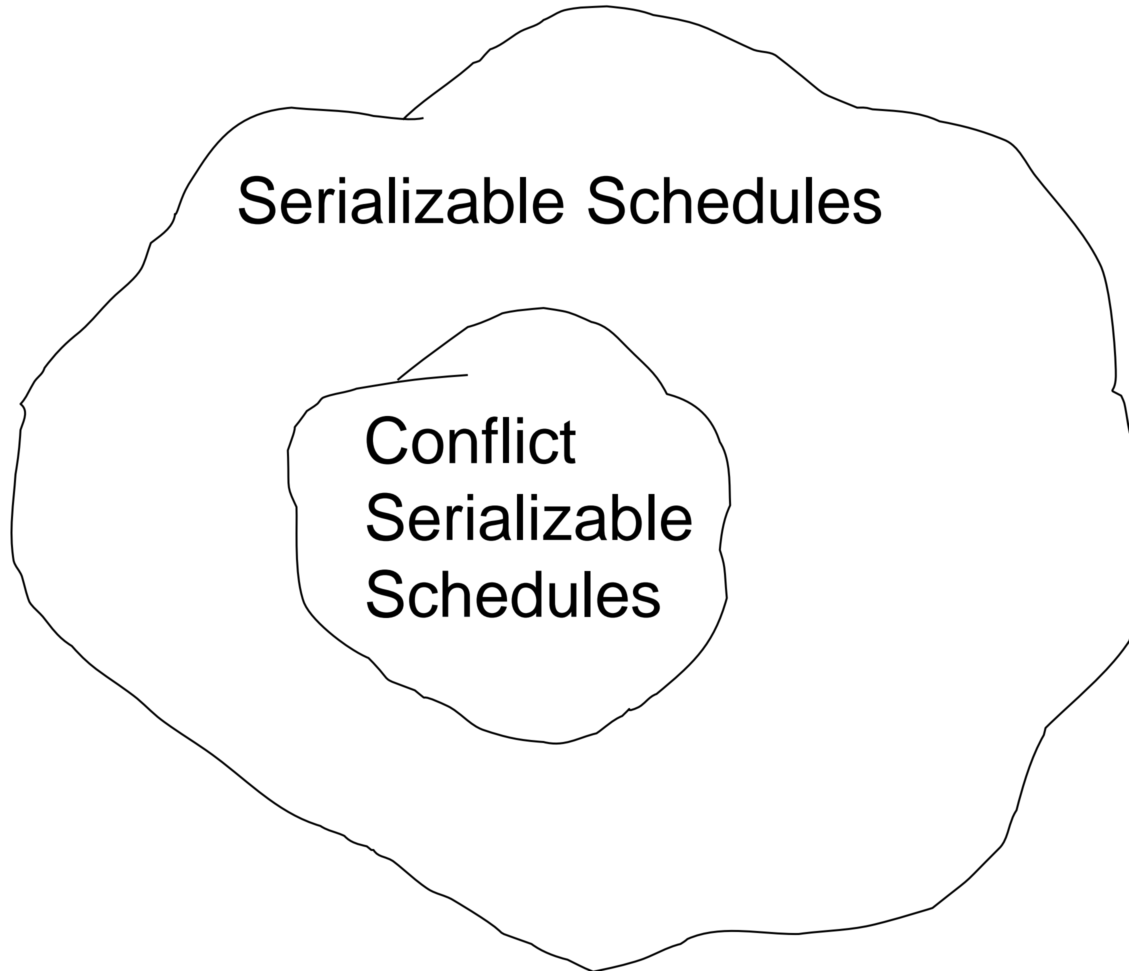


time

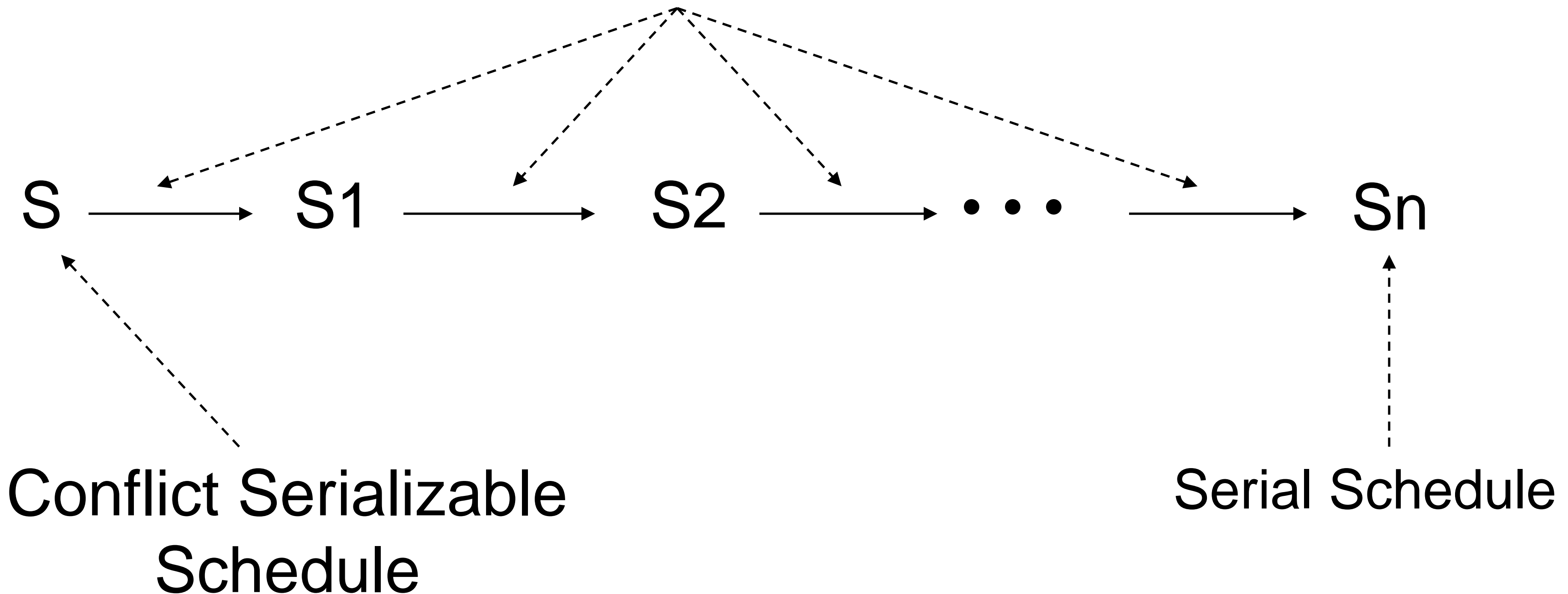
# Conflict Serializability

- Weaker notion of serializability
- Depends only on reads and writes

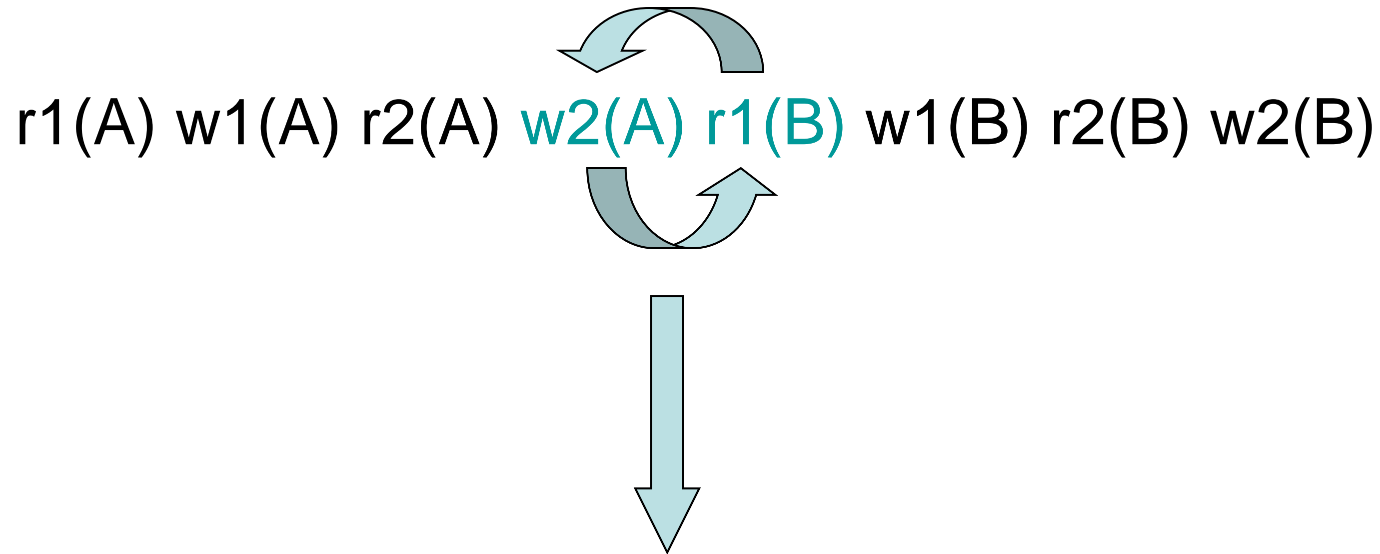
# Conflict Serializability



# Conflict Serializable Schedule



# Transformation: Example




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

# Non-Conflicting Actions

Two actions are non-conflicting if whenever they occur consecutively in a schedule, swapping them does not affect the final state produced by the schedule. Otherwise, they are conflicting.

# Conflicting or Non-Conflicting?

(Work on paper: Example 1)

# Conflicting Actions: General Rules

- Two actions of the same transaction conflict:
  - r1(A) w1(B)
  - r1(A) r1(B)
- Two actions over the same database element conflict, if one of them is a write
  - r1(A) w2(A)
  - w1(A) w2(A)

# Conflict Serializability Examples

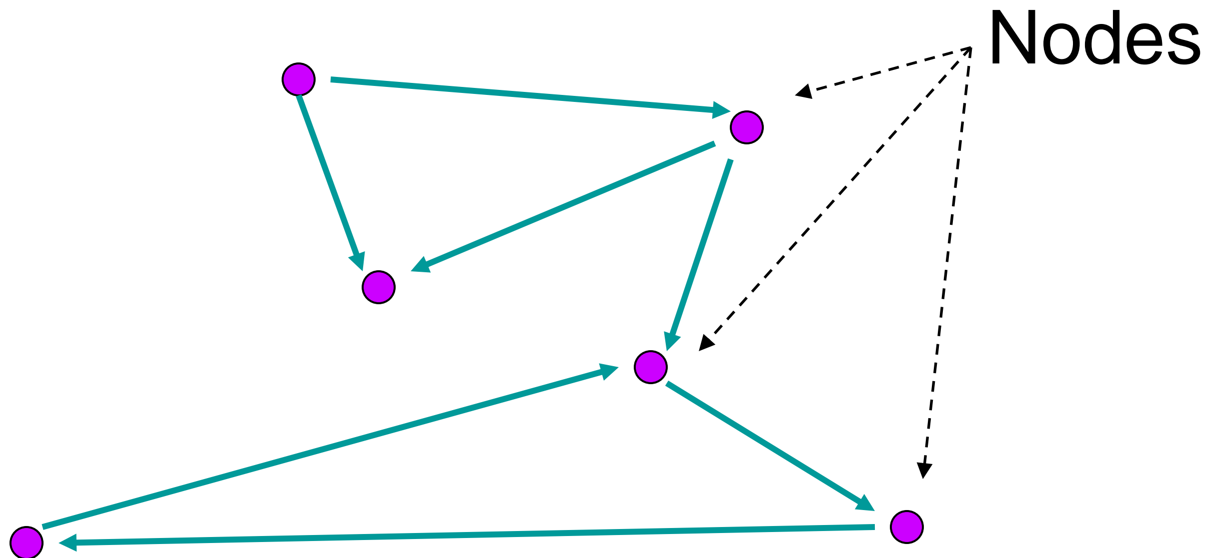
(Work on paper: Example 2 and 3)

# Testing Conflict Serializability

- Construct precedence graph G for given schedule S
- S is conflict-serializable iff G is acyclic

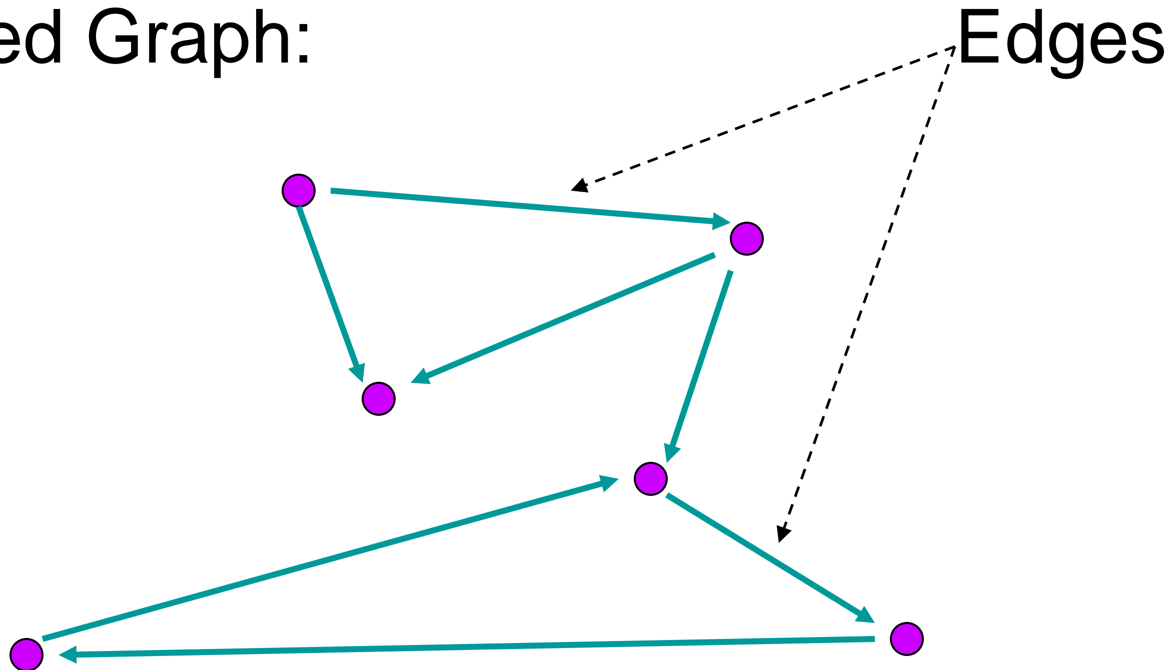
# Graph Theory 101

Directed Graph:



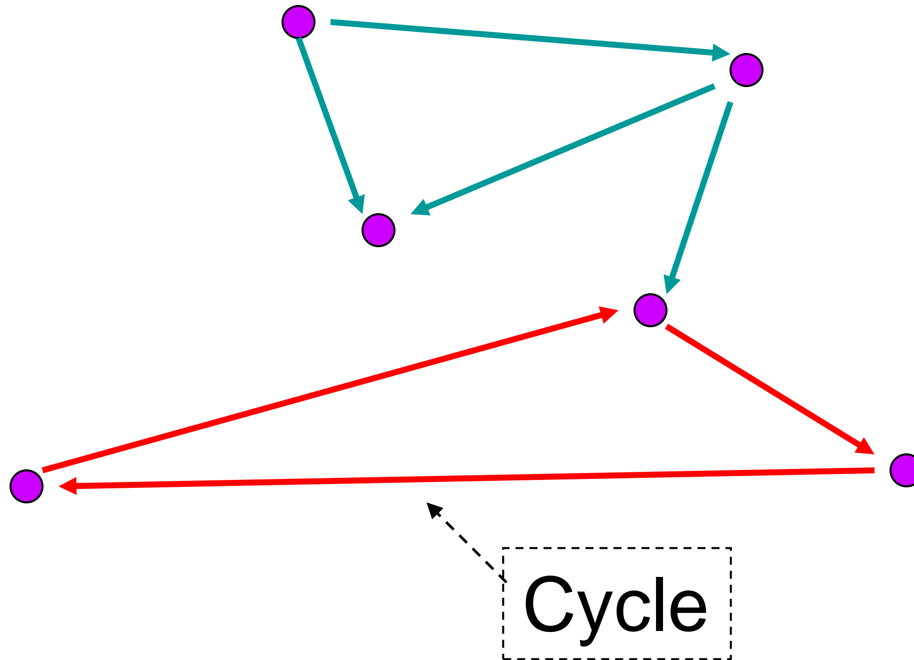
# Graph Theory 101

Directed Graph:



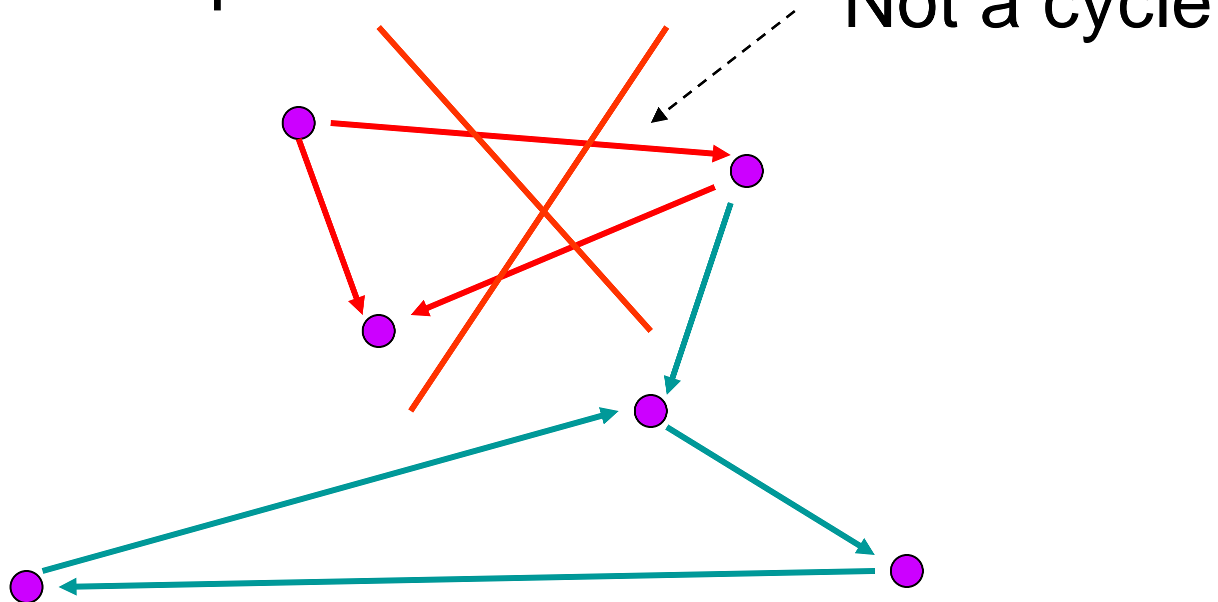
# Graph Theory 101

Directed Graph:



# Graph Theory 101

Directed Graph:

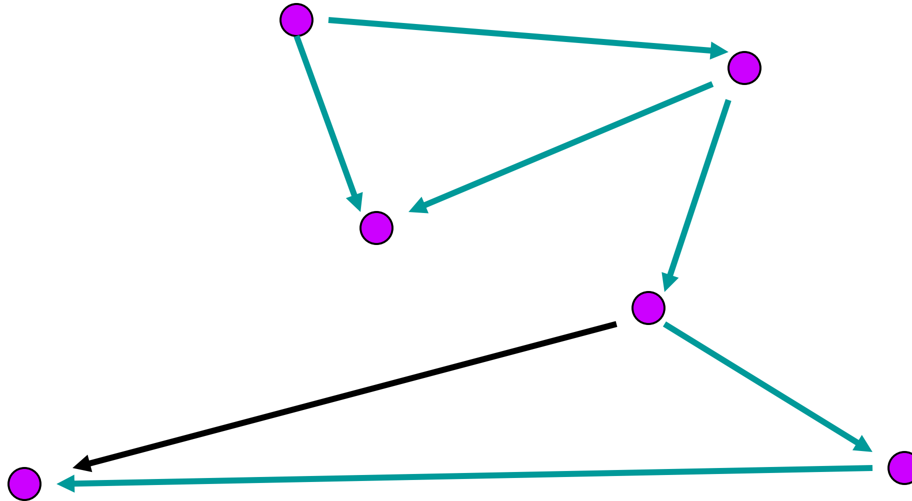


# Graph Theory 101

Acyclic Graph: A graph with no cycles

# Graph Theory 101

Acyclic Graph:

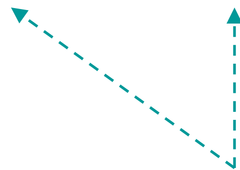


# Testing Conflict Serializability

- Construct precedence graph G for given schedule S
- S is conflict-serializable iff G is acyclic

# Precedence Graph

- Precedence graph for schedule S:
  - Nodes: Transactions in S
  - Edges: $T_i \rightarrow T_j$ whenever
    - S: … $r_i(X)$ … $w_j(X)$ …
    - S: … $w_i(X)$ … $r_j(X)$ …
    - S: … $w_i(X)$ … $w_j(X)$ …



Note: not necessarily consecutive

# Precedence Graph

- $T_i \rightarrow T_j$ whenever:
  - There is an action of Ti that occurs before a conflicting action of Tj.

# Precedence Graph Example

(Work on paper: Example 4)

# Testing Conflict Serializability

- Construct precedence graph G for given schedule S
- S is conflict-serializable iff G is acyclic

# Correctness of precedence graph method

(Work on paper)

# Serializability vs. Conflict Serializability

(Work on paper: Example 5)

# View Serializability

- A schedule S is view serializable if there exists a serial schedule S’, such that the source of all reads in S and S’ are the same.

# View Serializability Example

View Serializable Schedule

r2(B) w2(A) r1(A) r3(A) w1(B) w2(B) w3(B)

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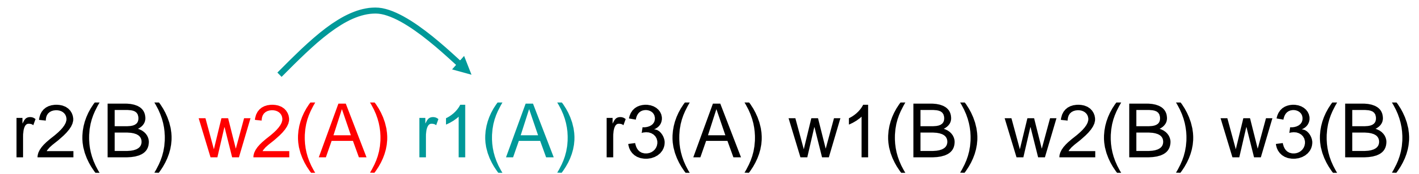
Serial Schedule

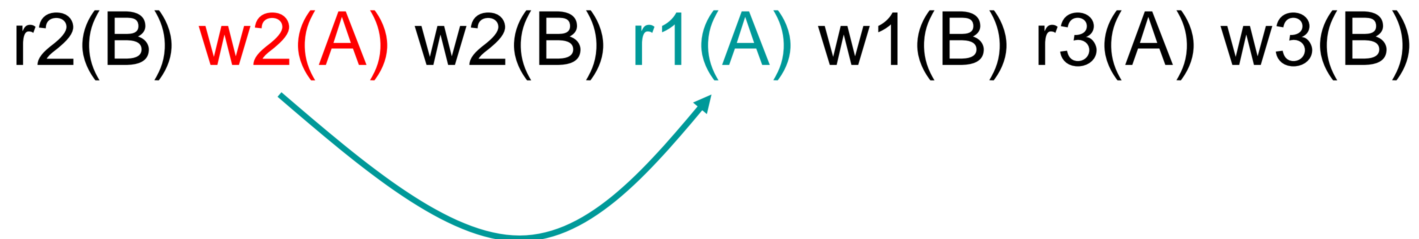
r2(B) w2(A) w2(B) r1(A) w1(B) r3(A) w3(B)

# View Serializability Example

View Serializable Schedule

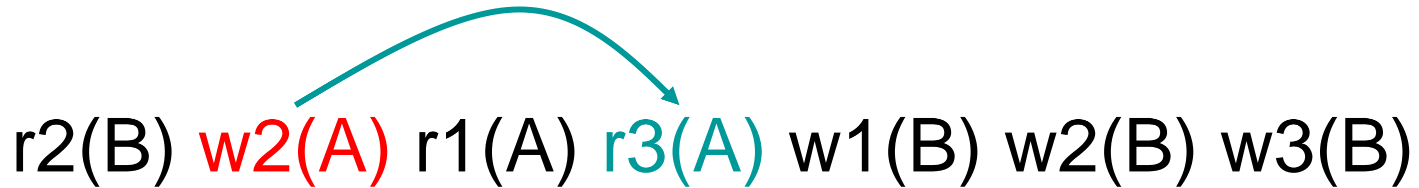



Serial Schedule

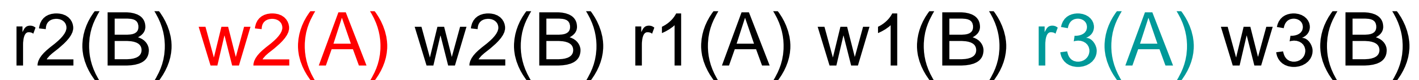


# View Serializability Example

View Serializable Schedule




Serial Schedule



# View Serializability Example

View Serializable Schedule

→ r2(B) w2(A) r1(A) r3(A) w1(B) w2(B) w3(B)

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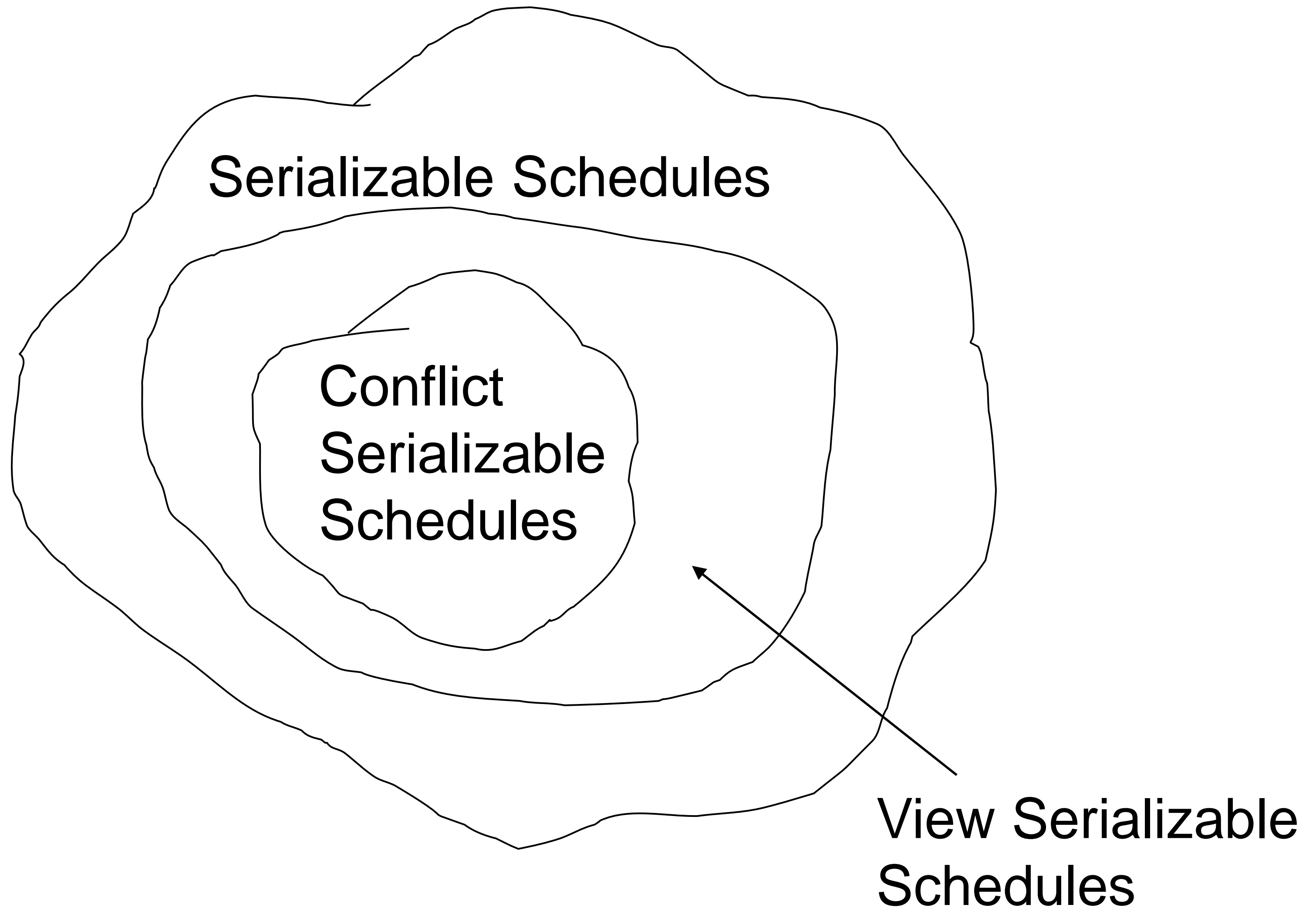
Serial Schedule

→ r2(B) w2(A) w2(B) r1(A) w1(B) r3(A) w3(B)

# View Serializability

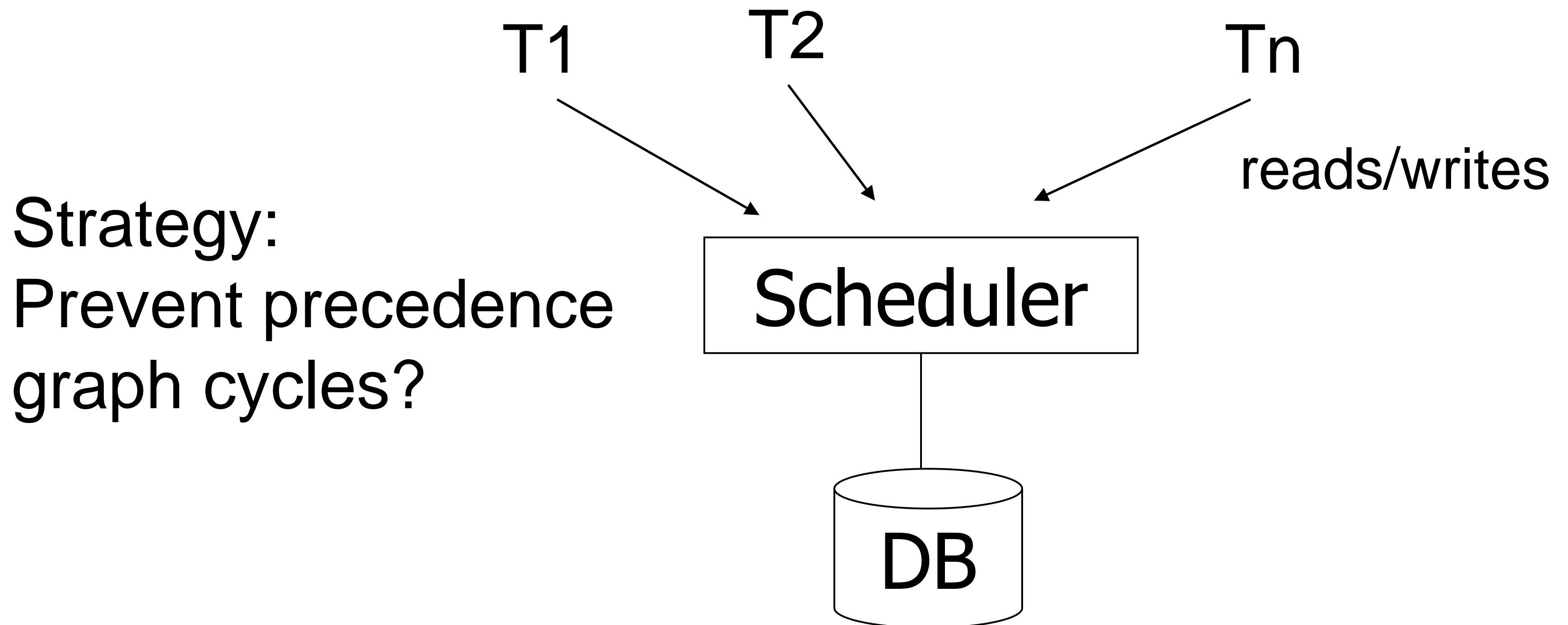


# Problems

- Which schedules are "correct"?
  - Serializability theory

- How to build a system that allows only "correct" schedules?
  - Efficient procedure to enforce ~~correctness~~ serializable schedules

# Enforcing Serializability



# Next

- Enforcing serializability
  - Locking-based techniques
  - Timestamp-based techniques
  - Validation-based techniques