Today:

- break planned ~13-13.10
- end planned ~ 13.50

(I have to give a talk after the lecture)

Concurrency Control

Databases, Aarhus University

Ira Assent

Intended learning outcomes

- Be able to
  - Determine serializable schedules
  - Apply the two-phase locking protocol

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Welcome to IADB students

- Instructor: Ira Assent
- "Super" TAs Pernille Matthews and Cheng Huang
- TAs for exercises classes and at **study café**
- **Lectures**: Tuesdays 12-14, Thursdays 10-12
  - **TA sessions** Tue afternoon –> Tue morning
- Weekly **handins** and multiple choice **exam** in June
  - Handins count for 20% of grade, exam for 80%
  - Need to sign up for handin groups (contact TA regarding enrollment)
- **Forum**: make good use of it: your questions here benefit everyone
- Please check "the to success" on homepage
- DBS pre-requisite
  - Access to earlier material from this year if you need to brush up
- See also details on brightspace page
- And for the rest of you: Welcome back after Easter!

Recap: Transactions

- Transaction
  - **Logical unit** of database processing
  - includes one or more operations on the database
- Basic operations are read and write
  - read_item(X)
    - Reads a database item named X
      - E.g. into a program variable
  - write_item(X)
    - Writes the value of database item X
  - We do not need any other information to understand the impact of transactions on the database state
    - I.e., which value a database item has, and which transaction has seen which value of a database item
- `BEGIN` or `START TRANSACTION`, `COMMIT`, `ROLLBACK`

  https://dev.mysql.com/doc/refman/8.0/en/commit.html
  https://dev.mysql.com/doc/refman/8.0/en/sql-transactional-statements.html

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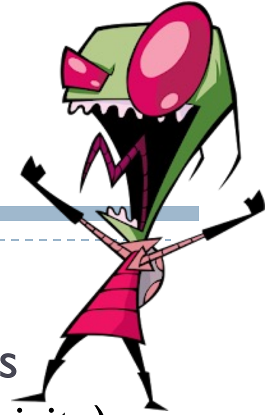
Recap: ACID



- DBMS supports **ACID** transactions
  - **Atomic** : Either the whole transaction process is done or none is
    - Any transaction does all its work on the database or none at all (atomicity)
      - so that there are no partial updates to the data or the like
  - **Consistent** : Database constraints are preserved
    - Any transaction that starts on a consistent database leaves it again in a consistent state; temporary inconsistency while it is still working is permitted;
      - so that there are no data integrity issues or the like
  - **Isolated** : It appears to user as if only one transaction process executes at a time
    - No transaction interferes with another
      - So that transactions do not produce conflicting results; looks like first one of the transactions has the database to itself until done, then the other
  - **Durable** : Effects of a process do not get lost if the system crashes
    - So that the changes made by a transaction actually persist and do not disappear
      - E.g. data is not actually written to the disk or the like

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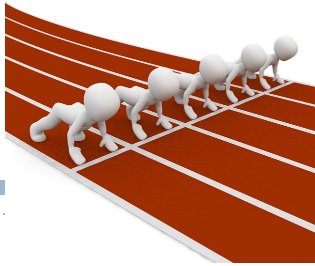
Concurrency control and schedules



- Goal of concurrency control: support more than one user / query at the same time
  - Sequential / serial: simply queue → slow
- Concurrent: allow access to database at the same time in interleaved fashion, but ensure same result
- **Schedule**: sequence of operations from one or more transactions
  - Operations considered: read(A), write (A) (start, commit, end, abort)
  - In concurrent transactions, the operations are interleaved

ACID: What is concurrency control mostly concerned with?

A. A, I
B. A, C
C. A, D
D. I, C
E. I, D
F. C, D

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Types of schedules

- **Serial** schedule:
  - Schedule S serial if, for every transaction T in S, all operations of T executed consecutively in S
    - Otherwise, **nonserial** schedule
  - Simplest case: each transaction gets its turn to have the database by itself, while others wait
- **Serializable** schedule:
  - Schedule S serializable if **equivalent** to some serial schedule of same transactions
  - Typically, operations of different transactions interweaved, but without creating issues
  - These are the kinds of schedules we want to create
    - Fast, multi-user access and **correct** result

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Example

- Database with two items, X and Y, program variables x, y
- Only criterion for correctness: X=Y
- Two concurrent transactions for programs

T_1: X := X + 1
Y := Y + 1

T_2: X := 2 * X
Y := 2 * Y

- Initially, X=10 and Y=10
- Serial schedule to the right:
  - execute first T_2 entirely, then T_1 entirely
    - Resulting database state:
      - X = 21, Y = 21, X = Y
  - Alternatively, first T_1, then T_2: X=Y=22

T_1	T_2
	read_item(X);
	X:=2*X;
	write_item(X);
	read_item(Y);
	Y:=2*Y;
	write_item(Y);
read_item(X);	
X:=X+1;	
write_item(X);	
read_item(Y);	
Y:=Y+1;	
write_item(Y);	

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Motivation for serializability

T_1	T_2
read_item(X);	
X:=X+1;	
write_item(X);	
	read_item(X);
	X:=2*X;
	write_item(X);
	read_item(Y);
	Y:=2*Y;
	write_item(Y);
read_item(Y);	
Y:=Y+1;	
write_item(Y);	

- Alternative concurrent schedule "incorrect": X=22, Y = 21, $X \neq Y$
- Concurrent execution of transactions **correct** if equivalent to some serial execution of those transactions
- For transactions T_1 and T_2 there are only two serial schedules: T_1, T_2 or T_2, T_1 and the result of this schedule is different from both of these
  - X=Y=21 or X=Y=22
  - Why? Because both T_1 and T_2 write X

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Defining equivalence of schedules

- When are two schedules **equivalent?**
  - In particular, we would like to understand if an interweaved schedule is equivalent to a serial schedule
- Two schedules are **result equivalent** if they produce the same final state of the database
  - This can happen by "accident" – state of the database is the same, but the operations differ → cannot be used to find the right schedules
- Instead, look at the operations in the transactions
  - Do they interfere with one another?
  - Notion of **conflict**

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Determining Serializability

- TAs T_i and T_j **conflict** iff there exists some item X, accessed by both T_i and T_j, and at least one of them wrote X
  - Intuitively, conflict between TAs forces an execution order between them
  - If there are no writes, the database state does not change, so no issue if both of them read it
- Let I and J be consecutive instructions by two different transactions within schedule S
  - If I and J do not conflict, may swap order to produce new schedule S‘
  - S and S' **conflict equivalent**
- Schedule **conflict serializable** if conflict equivalent to a serial schedule

Serializability

This schedule with an initial database satisfying X = Y is

A. Equivalent to a serial execution of T_3, T_4
B. Equivalent to a serial execution of T_4, T_3
C. Equivalent to a serial execution of T_3, T_4 and T_4, T_3
D. Not equivalent to a serial execution of T_3, T_4 or T_4, T_3

T_3	T_4
read_item(X);	
X:=X+1;	
	read_item(X);
write_item(X);	
	X:=2*X;
	write_item(X);
	read_item(Y);
	Y:=2*Y;
read_item(Y);	
Y:=Y+1;	
write_item(Y);	
	write_item(Y);

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Possible Transaction Conflicts

- **Write/Read conflict:**
  - T_2 must be executed after T_1, as T_2 reads value provided by T_1

T_1	T_2
write_item(X);	
	read_item(X);

- **Read/Write conflict:**
  - T_2 must be executed after T_1, as T_2 writes a new value after T_1 reads the old value

T_1	T_2
read_item(X);	
	write_item(X);

- **Write/Write conflict:**
  - T_2 must be executed after T_1, as T_2 overwrites value created by T_1

T_1	T_2
write_item(X);	
	write_item(X);

- **No conflict:**
  - no implied execution order of T_1 and T_2 as both read same value of X

T_1	T_2
read_item(X);	
	read_item(X);

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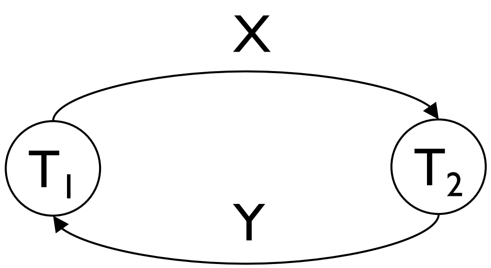
Precedence Graph (serialization graph)

- Directed graph depicting conflicts in schedule
  - Each transaction is a node
  - edge labeled X from T_i to T_j if T_i conflicts on X (and is before) T_j



T_1	T_2
read_item(X);	
X:=X+1;	
write_item(X);	
	read_item(X);
	X:=2*X;
	write_item(X);
	read_item(Y);
	Y:=2*Y;
	write_item(Y);
read_item(Y);	
Y:=Y+1;	
write_item(Y):	

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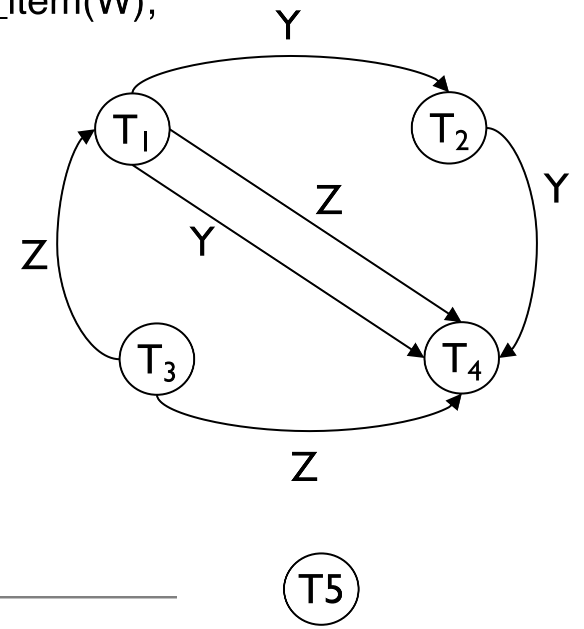
Is this precedence graph correct?

T_1	T_2	T_3	T_4	T_5
	read_item(X);			
read_item(Y);				
read_item(Z);				
				read_item(V);
				read_item(W);
				write_item(W);
	read_item(Y);			
	write_item(Y);			
		read_item(Z);		
		write_item(Z);		
read_item(U);				
			read_item(Y);	
			write_item(Y);	
			read_item(Z);	
			write_item(Z);	
read_item(U);				
write_item(U);				



A. No, T_5 is not connected
B. No, the label from T_2 to T_4 should be Z
C. No, T_2 should precede T_1
D. No, T_1 should precede T_3
E. No, arrows point the wrong way
F. Yes

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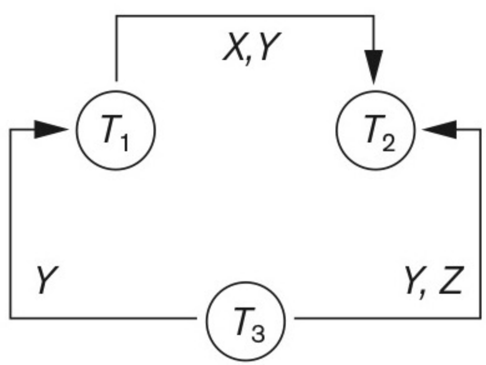
Textbook Example of Serializability Testing

Time

Transaction T_1	Transaction T_2	Transaction T_3
		read_item(Y); read_item(Z);
read_item(X); write_item(X);		
		write_item(Y); write_item(Z);
	read_item(Z);	
read_item(Y); write_item(Y);		

	read_item(Y);
	write_item(Y);
	read_item(X);
	write_item(X);	



Equivalent serial schedules

$T_3 \rightarrow T_1 \rightarrow T_2$

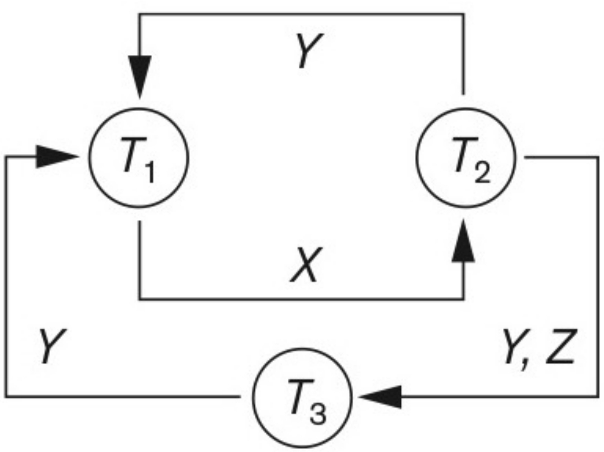
Another Example of Serializability Testing

Time

Transaction T_1	Transaction T_2	Transaction T_3

	read_item(Z);
	read_item(Y);
	write_item(Y);	

		read_item(Y); read_item(Z);
read_item(X); write_item(X);		
		write_item(Y); write_item(Z);
	read_item(X);	
read_item(Y); write_item(Y);		
	write_item(X);	



Equivalent serial schedules

None

Reason

Cycle $X(T_1 \rightarrow T_2), Y(T_2 \rightarrow T_1)$

Cycle $X(T_1 \rightarrow T_2), YZ\ (T_2 \rightarrow T_3), Y(T_3 \rightarrow T_1)$

Testing Serializability

- Test: schedule is (conflict) serializable if its precedence graph is acyclic
- Topological sorting gives a serialization order
- Need to guarantee serializability
  - An inefficient strategy
    - Generate a schedule, build the precedence graph, and test for cycle
    - If cycle found, need to generate another schedule, …

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Determining serializability

- Serializability hard to check
  - Interleaving of operations in operating system through some scheduler
  - Difficult to determine beforehand how operations in schedule will be interleaved

Practical approach:

- Devise **protocols** (methods) to ensure serializability
- Not possible to determine when schedule begins and ends
  - "the database never sleeps" – endless stream of transactions

  - Reduce the problem of checking the whole schedule to checking only a **committed projection** of the schedule
    - i.e. operations from only the committed transactions
- Current approach used in most DBMSs:
  - Use of locks with two phase locking

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Locks for concurrency control

- Locking is an operation which secures
  - (a) permission to read and/or
  - (b) permission to write a data item for a transaction
  - **Lock (X)**: data item X is locked in behalf of the requesting transaction, so it obtains access permission
- Unlocking is an operation which removes these permissions from the data item
  - **Unlock (X)**: data item X is made available to all other transactions
- Lock and Unlock are atomic operations
- Transaction must be **well-formed**:
  - It must lock the data item before it reads or writes to it
  - It must not lock an already locked data item and it must not try to unlock a free data item
- Lock Manager maintains lock table with information on (at least) data items with locks currently granted, queue for waiting transactions

Lock modes

- Two **locks modes**:
- Shared mode: **shared lock (X)** or **read lock (X)**
  - More than one transaction can apply shared lock on X for reading its value, but no write lock can be applied on X by any other transaction
- Exclusive mode: **exclusive lock (X)** or **write lock (X)**
  - Only one write lock on X can exist at any time and no shared lock can be applied by any other transaction on X
- Conflict matrix
  - Same as for conflict serializability

	Read	Write
Read	Y	N
Write	N	N

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The Two-Phase Protocol

- Phase 1 (*growing phase*):
  - Transaction may request locks
  - Transaction may not release locks
- Phase 2 (*shrinking phase*):
  - Transaction may not request locks
  - Transaction may release locks
- When the first lock is released, the transaction moves from phase 1 to phase 2

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Two-Phase With Lock Conversion

- First phase
  - Can acquire a shared lock on item X
  - Can acquire an exclusive lock on item X
  - Can **convert (upgrade)** a shared lock on X to an exclusive lock on X
- Second phase
  - Can release a shared lock
  - Can release an exclusive lock
  - Can **convert (downgrade)** an exclusive lock to a shared lock
- This protocol assures serializability

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Practical Two-Phase Protocol (2PL)

- Transaction issues standard read/write instructions
- System manages protocol, including lock operations

read X: if T has a lock on X
    perform read
else
    wait until no other transaction has write_lock(X)
    grant read_lock(X) to T
    perform read

write X: if T has a write_lock(X)
    perform write
else
    wait until no other transaction has a lock on X
    if T has read_lock(X)
        convert it to write_lock(X)
    else grant it write_lock(X)
    perform write

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2PL?

A. Yes, follows 2PL
B. No, phases not separate
C. Yes, if lock conversion is applied
D. No, there is a conflict

Time ↓

T_1	T_2
read_lock (Y);	
read_item (Y);	
unlock (Y);	
	read_lock (X);
	read_item (X);
	unlock (X);
	write_lock (Y);
	read_item (Y);
	Y:=X+Y;
	write_item (Y);
	unlock (Y);
write_lock (X);	
read_item (X);	
X:=X+Y;	
write_item (X);	
unlock (X);	

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Textbook locking example

Time

T_1	T_2
read_lock (Y);	
read_item (Y);	
unlock (Y);	
	read_lock (X);
	read_item (X);
	unlock (X);
	write_lock (Y);
	read_item (Y);
	Y:=X+Y;
	write_item (Y);
	unlock (Y);
write_lock (X);	
read_item (X);	
X:=X+Y;	
write_item (X);	unlock (X);

This is **NOT** 2PL, as e.g. T_1 unlocks Y and then locks X
→ would not be allowed to run

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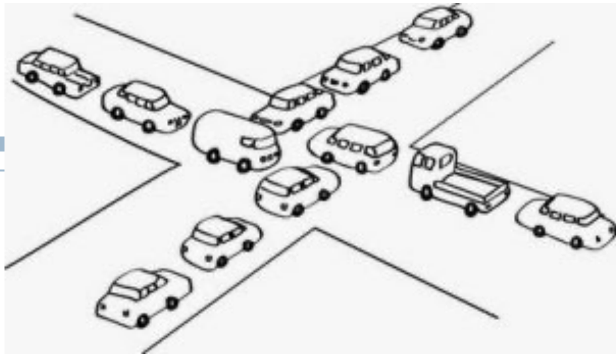
Textbook example: 2PL



T_1	T_2
read_lock (Y);	
	read_lock (X);
read_item (Y);	read_item (X);
	write_lock (Y);
write_lock (X);	
unlock (Y);	
	unlock (X);
read_item (X);	read_item (Y);
X:=X+Y;	Y:=X+Y;
write_item (X);	write_item (Y);
unlock (X);	**unlock (Y);**

- Now 2PL policy followed, but **deadlock**
  - T_1 cannot get write_lock(X) as T_2 has read_lock(X) and T_2 cannot get write_lock(Y) as T_1 has read_lock(Y)

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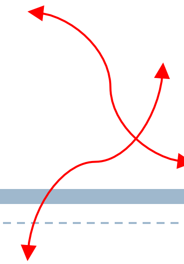
Deadlocks



- **Deadlock**
  - A cycle of transactions waiting for one another's unlock (cycle wait)
- **Deadlock prevention**
  - A transaction locks all data items it refers to before it begins execution
    - prevents deadlock since a transaction never waits for a data item
    - Impractical: usually necessary data items not fully known
- **Deadlock detection and resolution**
  - Scheduler maintains wait-for-graph for detecting cycles
    - if transaction is blocked, add to graph
    - chain like T_i waits for T_j waits for T_k waits for T_i creates cycle
- **Deadlock avoidance**
  - Avoid deadlock by not letting the cycle complete
    - When blocking transaction likely to create a cycle, abort the transaction
- **Starvation** means transaction consistently waits or restarts and never completes
  - In deadlock resolution, same transaction may repeatedly be victim and aborted

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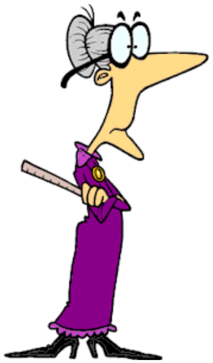
Practical deadlock prevention

- Prevent deadlocks when a requested lock cannot be obtained
  - Based on the timestamp (“age”) of transaction: when did it enter?
  - **Wait-die**: older transaction may wait for younger transaction, younger transaction waiting for older transaction is aborted
    - Has not yet been running as long, expect fewer resources are wasted
  - **Wound-wait**: younger transaction may wait for older one, an older transaction will preempt the younger one, i.e., younger one aborted as well
  - Both techniques handle deadlocks and restart the younger transaction
    - Still, may abort transactions that are not actually deadlocked
  - **No waiting**: as soon as lock cannot be obtained, abort transaction, restart with some delay
    - No deadlocks, but may cause many unnecessary aborts and restarts
  - **Cautious waiting**: if lock cannot be obtained, abort only if the transaction that has the conflicting lock is waiting, else wait
    - Also, no deadlocks

Versions of 2PL

- **Basic**
  - Transaction locks data items incrementally
    - may cause deadlock which is dealt with
- **Strict**
  - Exclusive locks unlocked after terminating (commit / abort and rollback)
    - most commonly used two-phase locking algorithm
- **Rigorous**
  - All unlocking (shared and exclusive) after terminating (commit / abort and rollback)
- **Conservative**
  - Prevent deadlock by locking all desired data items before start of transaction
    - Often not realistic / efficient: as part of execution, determine which data items needed; if not requested from beginning, need to abort and start over



A working example: 2PL

2PL: growth phase (acquire locks), then shrink phase (release locks)

T_1	T_2
read_lock (X);	
read_item (X);	
	read_lock (X);
	read_item (X);
read_lock(Y);	
write_lock (Y);	
unlock (X);	
	write_lock(X);
	write_item(X);
write_item (Y);	
unlock (Y);	
	read_lock(Y);
commit;	
	read_item (Y);
	write_lock (Y);
	unlock (X);
	write_item(Y);
	unlock (Y);
	commit;

2PL basic: unlock immediately when entering 2nd phase

T_1	T_2
read_lock (X);	
read_item (X);	
	read_lock (X);
	read_item (X);
read_lock(Y);	
write_lock (Y);	
unlock (X);	
	write_lock(X);
	write_item(X);
write_item (Y);	
commit;	
unlock (Y);	
	read_lock(Y);
	read_item (Y);
	write_lock (Y);
	write_item(Y);
	commit;
	unlock (X);
	unlock (Y);

2PL strict: unlock exclusive locks when terminating

T_1	T_2
read_lock (X);	
read_item (X);	
	read_lock (X);
	read_item (X);
read_lock(Y);	
write_lock (Y);	
write_item (Y);	
commit;	
unlock (X);	
	write_lock(X);
	write_item(X);
unlock (Y);	
	read_lock(Y);
	read_item (Y);
	write_lock (Y);
	write_item(Y);
	commit;
	unlock (X);
	unlock (Y);

2PL rigorous: unlock when terminating

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Aggressive versus Conservative Protocols

- **Aggressive Protocols**
  - Proceed as quickly as possible even if situation may lead to aborts later
  - Example: our practical 2-phase lock conversion protocol

- **Conservative protocols**
  - Do not do work that may later have to be undone
  - Example: each transaction requests all locks it will ever need at the beginning, and they are held until the end of the transactions
    - No deadlock!
    - Livelock (also called starvation) avoided by queuing lock requests
    - Disadvantage - more waiting, loss of concurrency

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Intended learning outcomes

- Be able to
  - Determine serializable schedules
  - Apply the two-phase locking protocol

Acknowledgements: includes slide material by Jeff Ullman, Torben Bach Pedersen, and teachcoop

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What was this all about?

Guidelines for your own review of today's session

- Concurrency control allows transactions to…
- A schedule is…
  - It is serial if…
- A conflict between transactions is…
  - A precedence graph shows conflicts by…
  - A (conflict-)serializable schedule is…
- The two-phase locking protocol consists of…
  - It guarantees that… because…
  - The difference between a shared and exclusive lock is…
- Deadlocks are…
  - They can happen if…
- Starvation means…
  - It occurs when…

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