CS 370: OPERATING SYSTEMS
[ATOMIC TRANSACTIONS]

On transactions, logs, and recovery
Something to write?
Play nice
Record it twice
Lest lurking failures bite

Transactions you commit
To a log
A perpetual epilogue
That grows tail-side bit by bit

At recovery's dawn
The log's a looking glass
Of what's come to pass
Helping invert that frown

Informing what's to be redone
And what's to be undone

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Topics covered in today's lecture

- Synchronization examples
- Atomic transactions

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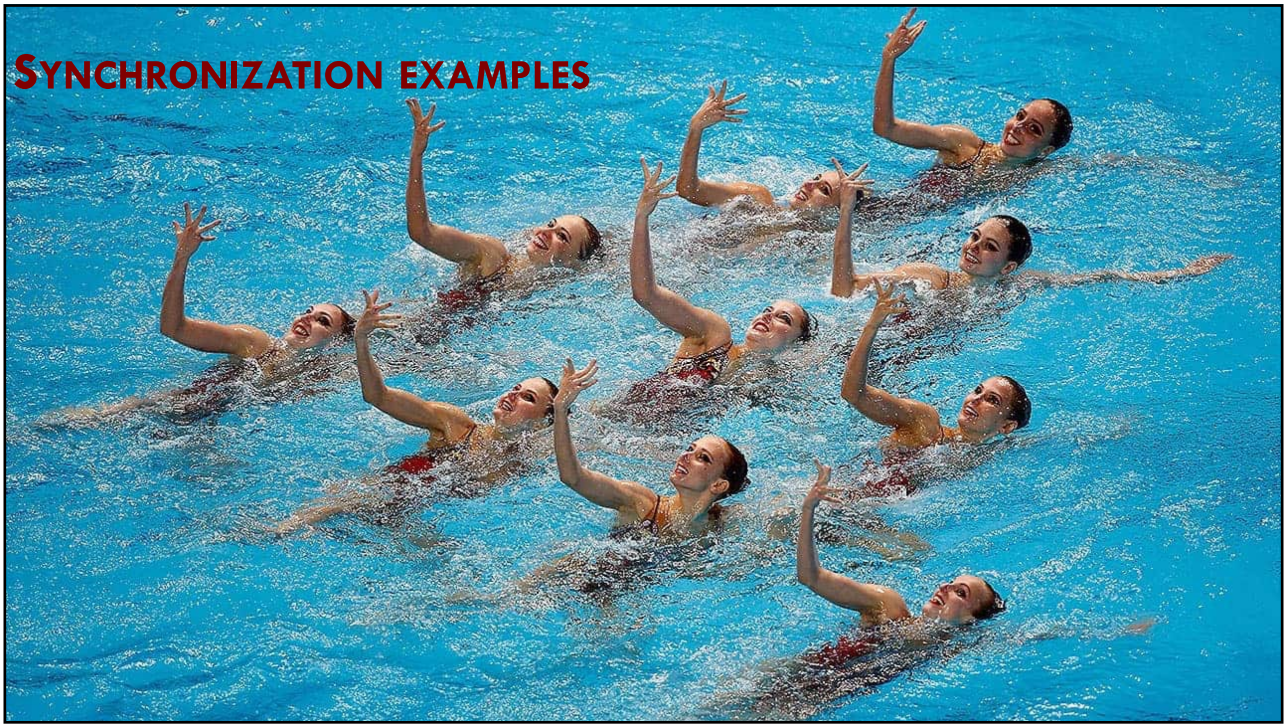

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Synchronization in Solaris

- Condition variables
- Semaphores
- Adaptive mutexes
- Reader-writer locks
- Turnstiles

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Synchronization in Solaris: Adaptive mutex

- Starts as a standard semaphore implemented as spinlock
- On **SMP systems** if data is locked and in use?
  - If lock held by thread on another CPU
    - Spin waiting for lock to be available
  - If thread holding the lock is not in the *run* state
    - Block until awakened by release of the lock

Adaptive mutex: On a single processor system

- Only one thread can run at a time
- So, thread sleeps (instead of spinning) when a lock is encountered

Adaptive mutex is used only for short code segments

- Less than a **few hundred** instructions
  - Spinlocks inefficient for code segments larger than that
- Cheaper to put a thread to sleep and awaken it
  - Busy waiting in the spinlock is expensive
- Longer code segments?
  - Condition variables and semaphores used

Reader-writer locks

- Used to protect data accessed **frequently**
  - *Usually* accessed in a read-only manner
- Multiple threads can read data **concurrently**
  - Unlike binary semaphores that *serialize* access to the data
- Relatively expensive to implement
  - Used only on long sections of code

Solaris: Turnstiles

- **Queue structure** containing threads blocked on a lock
- Used to order threads waiting to acquire adaptive mutex or reader-writer lock
- Each **kernel thread has its own turnstile**
  - As opposed to every synchronized object
  - Thread can be blocked only on one object at a time

Solaris: Turnstiles

- Turnstile for the first thread to block on synchronized object
  - Becomes turnstile for the object itself
  - Subsequent threads blocking on lock are added to this turnstile
- When this first thread releases its lock?
  - It *gains a new turnstile* from the list of free turnstiles maintained by kernel

Turnstiles are organized according to the priority inheritance protocol

- If the thread is holding a lock on which a higher priority thread is blocked?
  - Will *temporarily inherit* priority of higher priority thread
  - *Revert back* to original priority after releasing the lock

Linux: Prior to 2.6, Linux was a nonpreemptive kernel

- Provides spinlocks and semaphores

Single processor	Multiple processors
Disable kernel preemption	Acquire spinlock
Enable kernel preemption	Release spinlock

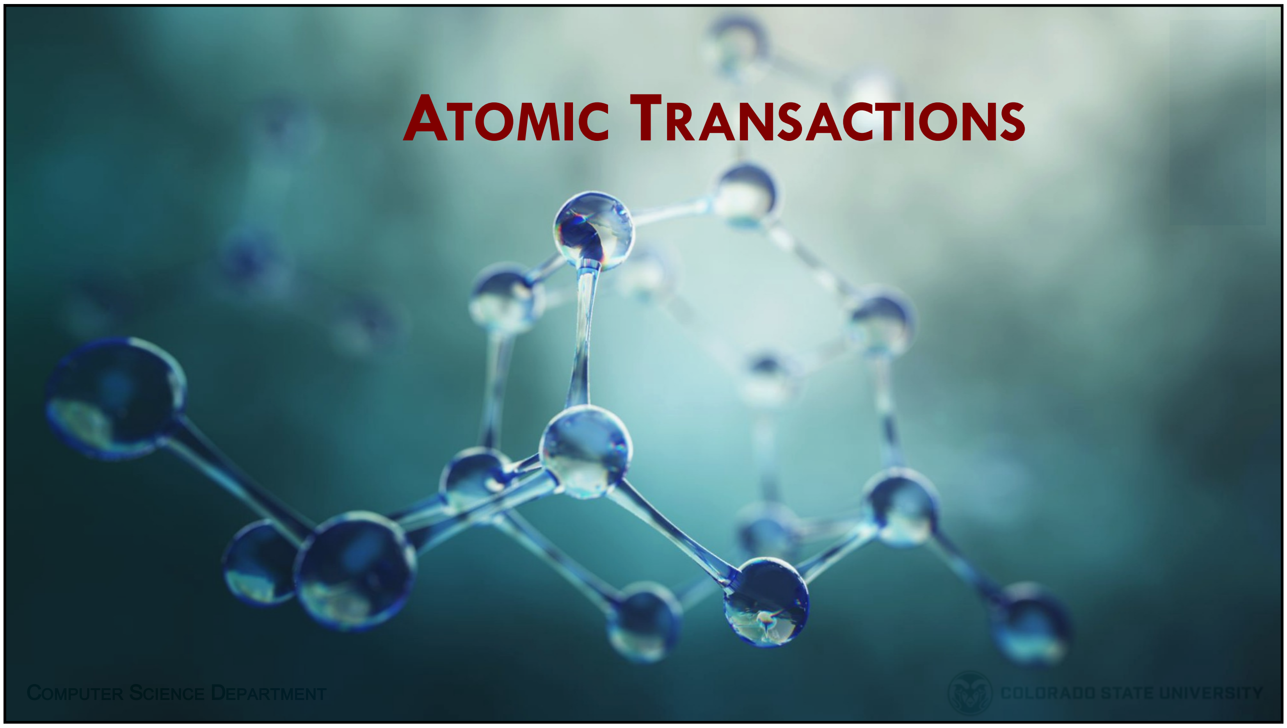
17 December 2003 - Linux 2.6.0 was released (5,929,913 lines of code)
4 January 2011 - Linux 2.6.37 was released (13,996,612 lines of code)
Version: 4.10.1 [stable version] (~18,000,000 lines of code)
Version 6.1 Feb 2023 (~35,550,0000 lines of code)

Kernel is not preemptible if a kernel-mode task is holding a lock

- Each task has a `thread-info` structure
  - Counter `preempt_count` indicates number of locks being held by task
  - `preempt_count` incremented when lock acquired
    - Decremented when lock released
  - If is `preempt_count > 0`; not safe to preempt
    - OK otherwise; if no `preempt_disable()` calls pending

Linux: Other mechanisms

- Atomic integers `atomic_t`
  - All math operations using atomic integers are performed without interruption
  - E.g.: set, add, subtract, increment, decrement
- Mutex locks
  - `mutex_lock()`: Prior to entering critical section
  - `mutex_unlock()`: After exiting critical section
  - If lock is unavailable, task calling `mutex_lock()` is put to sleep
    - Awakened when another task calls `mutex_unlock()`



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Atomic transactions

- Mutual exclusion of critical sections ensures their atomic execution
  - As one *uninterruptible unit*

- Also, important to ensure that critical section forms a **single logical unit of work**
  - Either work is performed in **its entirety or not at all**
  - E.g., transfer of funds
    - Credit one account and debit the other

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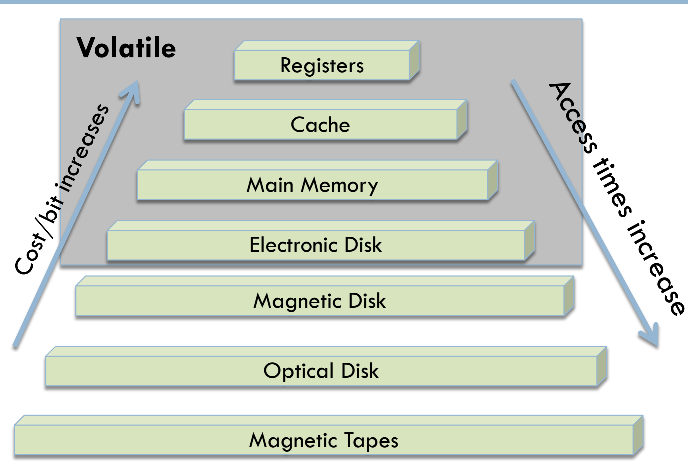
Transaction

- Collection of operations performing a **single logical function**
- Preservation of **atomicity**
  - Despite the possibility of failures

Storage system hierarchy based on speed, cost, size and volatility



A transaction is a program unit that accesses/updates data items on disk

- Simply a sequence of read and write operations
  - Terminated by commit or abort
- **Commit**: Successful transaction termination
- **Abort**: Unsuccessful due to
  - Logical error or system failure

Transaction rollbacks

- An aborted transaction may have **modified** data
- State of accessed data must be **restored**
  - *To what it was* before transaction started executing

Log-based recovery to ensure atomicity: **Rely on stable storage**

- Record info describing **all** *modifications* made by transaction to various accessed data.
- Each log record describes a **single** write
  - Transaction name
  - Data item name
  - Old value
  - New value
- Other log records exist to record significant events
  - Start of transaction, commit, abort, etc.

Actual update cannot take place prior to the logging

- Prior to `write(X)` operation
  - Log records for **X** should be written to stable storage
- Two physical writes for every logical write
  - More storage needed
- Functionality worth the price:
  - Data that is extremely **important**
  - For **fast** failure recovery

Populating entries in the log

- Before transaction T_i starts execution
  - Record <T_i starts> written to the log
- Any write by T_i is **preceded** by writing to the log
- When T_i commits
  - Record <T_i commits> written to log

The system can handle any failure without loss of information: Log

- undo(T_i)
  - **Restores** value of all data updated by T_i to **old** values
- redo(T_i)
  - Sets value of all data updated by T_i to **new** values
- undo(T_i) and redo(T_i)
  - Are **idempotent**
  - Multiple executions have the *same result* as 1 execution

If system failure occurs restore state by consulting the log

- Determine which transactions need to be *undone*; and which need to be *redone*
- T_i is undone if log
  - Contains <T_i starts> but no <T_i commits> record
- T_i is redone if log
  - Contains both <T_i starts> and <T_i commits>

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Rationale for checkpointing

- When failure occurs we consult the log for undoing or redoing
- But if done naively, we need to search *entire* log!
  - Time consuming
  - Recovery takes longer
    - Though no harm done by redoing (idempotency)

In addition to write-ahead logging, periodically perform checkpoints

- Output the following to stable storage
  - All log records residing in main memory
  - All modified data residing in main memory
  - A log record `<checkpoint>`
- The `<checkpoint>` allows a system to **streamline** recovery procedure

Implications of the checkpoint record

- T_i committed prior to checkpoint
  - <T_i commits> appears before <checkpoint>
  - Modifications made by T_i *must have been written* to stable storage
    - Prior to the checkpoint or
    - As part of the checkpoint
- At recovery no need to redo such a transaction

Refining the recovery algorithm

- Search the log **backward** for first checkpoint record.
  - Find transactions T_i *following* the last checkpoint
  - redo and undo operations applied *only* to these transactions

Looking at the log to determine which one to redo and which one to undo

<T1 starts>
<T1 … write record>
<T1 aborts>

<T2 starts>
<T2 … write record>
<T2 commits>

<checkpoint>
<T3 starts>
<T3 … write record>
….
<checkpoint>
<T4 starts>
<T4 … write record>
<T4 commits>

<T5 starts>
<T5 ..write record>

T4 will be redone

T5 will be undone

? Transactions?

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CONCURRENT ATOMIC TRANSACTIONS

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Concurrent atomic transactions

- Since each transaction is atomic
  - Executed serially in some arbitrary order
    - **Serializability**
  - Maintained by executing each transaction within a critical section
    - Too restrictive
- Allow transactions to **overlap** while maintaining serializability
  - **Concurrency control algorithms**

Serializability

- Serial schedule: Each transaction executes atomically

  $n!$ schedules for n transactions

T0	T1
read(A)	
write(A)	
read(B)	
write(B)	
	read(A)
	write(A)
	read(B)
	write(B)

Non-serial schedule: Allow two transactions to overlap

- Does not imply incorrect execution
  - Define the <u>notion of conflicting operations</u>
- O_i and O_j **conflict** if they access same data item
  - AND at least one of them is a `write` operation
- If O_i and O_j do not conflict; we can ***swap*** their order
  - To create a new schedule

Concurrent serializable schedule

T0	T1
read(A)	
write(A)	
read(B)	
write(B)	
	read(A)
	write(A)
	read(B)
	write(B)

Serial Schedule

T0	T1
read(A)	
write(A)	
	read(A)
	write(A)
read(B)	
write(B)	
	read(B)
	write(B)

Conflict serializability

- If schedule **S** can be **transformed** into a serial schedule **S'**
  - By a series of swaps of non-conflicting operations

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Locking protocol governs *how* locks are acquired and released

- There are different **modes** in which data can be locked
  - A transaction acquires a lock on a data item in different modes
- **Shared** mode locks
  - T_i can read, but not write, data item Q
- **Exclusive** mode locks
  - T_i can read and write data item Q

Transactions must request locks on data items in the right mode

- To **access** data item Q; T_i must first **lock** it
  - Wait if Q is locked in the exclusive mode
  - If T_i requests a shared-lock on Q
    - Obtain lock if Q is not locked in the *exclusive* mode
- T_i *must hold* lock on data item as long as it accesses it

Two-phase locking protocol: Locks and unlocks take place in two phases

- Transaction's **growing** phase:
  - Obtain locks
  - *Cannot release* any lock
- Transaction's **shrinking** phase
  - Can release locks
  - *Cannot obtain* any new locks

Two-phase locking protocol: Conflict serializability

- Conflicts occur when 2 transactions access same data item; and 1 of them is a write
- A transaction acquires locks serially; *without* releasing them during the acquire phase
  - Other transactions must wait for first transaction to start releasing locks
- Deadlocks may occur

Order of conflicting transactions

- Two-phase locking
  - Determined at **execution** time
- How about selecting this order in *advance*?
  - **Timestamp based protocols**

Timestamp based protocols

- For each T_i there is a fixed timestamp
  - Denoted $TS(T_i)$
  - Assigned before T_i starts execution
- For a later T_j ; $TS(T_i) < TS(T_j)$
- Schedule must be equivalent to schedule in which T_i appears before T_j.

Timestamp based locking

- Protocol ensures there will be **no deadlock**
  - No transaction ever waits!
- Conflict serializabilty
  - Conflicting operations are processed *in timestamp order*

Each data item Q has two values

- `W-timestamp(Q)`
  - Largest timestamp of any transaction that successfully executed `write()`
- `R-timestamp(Q)`
  - Largest timestamp of any transaction that successfully executed `read()`

Transaction issues a `read(Q)`

- If $TS(T_i) <$ `W-timestamp(Q)`
  - Needs value that was already *overwritten*
  - The `read` is rejected and T_i is rolled back
- $TS(T_i) >=$ `W-timestamp(Q)`
  - Operation is executed
  - `R-timestamp(Q)=` **max**`(TS(`T_i`),R-timestamp(Q))`

The key idea here is that when a transaction executes none of the data items must be from the future.

Transaction issues a `write(Q)`

- If $TS(T_i) <$ `R-timestamp(Q)`
  - Value of Q produced by T_i needed *previously*
    - T_i assumed that this value would never be produced
  - The `write` is rejected and T_i is rolled back
- If $TS(T_i) <$ `W-timestamp(Q)`
  - Trying to write an **obsolete** value of Q
  - The `write` is rejected and T_i is rolled back

What happens when a transaction is rolled back?

- Transactions T_i is assigned a new timestamp
  - Restart

Schedule using the timestamp protocol:

T2	T3
read(B)	
	read(B)
	write(B)
read(A)	
	read(A)
	write(A)

Timestamps are assigned to transactions before the start of the first instruction `TS(T2) < TS(T3)`

The contents of this slide-set are based on the following references

- *Avi Silberschatz, Peter Galvin, Greg Gagne. Operating Systems Concepts, 9th edition. John Wiley & Sons, Inc. ISBN-13: 978-1118063330.* [Chapter 5]