IPADS INSTITUTE OF PARALLEL AND DISTRIBUTED SYSTEMS

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

Before-or-after atomicity and Serializability

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Review: what is a strong consistency model

It's easy for users to reason about correctness assuming

- Everything has only one-copy
- The overall behavior is equivalent to some serial behavior
- The operations that need to be executed in an atomic unit (usually called operations belonging to a transaction) are executed on a machine **that happens completely or not at all (all-or-nothing atomicity)**

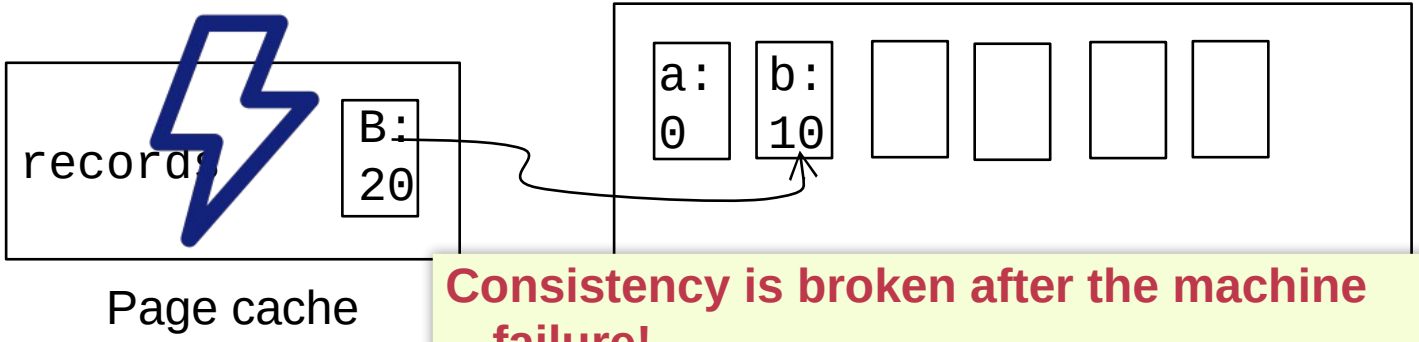
All-or-nothing atomicity makes it much easier to reason about failures

- Need to think about the consequences of the action happening or not happening, but not about the action ***partially*** happening

Review: why we need all or nothing atomicity?

```
transfer(bank, a, b, amt): // amt=10
    records = mmap(bank, ...)
    records[a] = records[a] – amt
    records[b] = records[b] + amt
    fsync(bank, ...)
```

① Write(A)
② Write(B)



Page cache

Consistency is broken after the machine failure!

Application invariant that must preserve:
bank(a) + bank(b) never changes

Review: techniques to support all-or-nothing

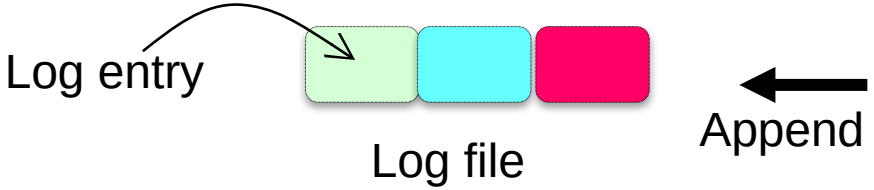
Systematic methods to support all-or-nothing atomicity

- Shadow copy (Single-file updates)
- Journaling (Filesystem API)

Logging

- REDO logging (A general-purpose approach)

Review: redo-only logging




```
transfer(bank, a, b, amt, log): // amt=10
    records = mmap(bank, ...)
    new_a = records[a] – amt
    new_b = records[b] + amt

    commit_log = "log start: a:" + new_a + "\b:" +
new_b
    log.append(commit_log).sync()

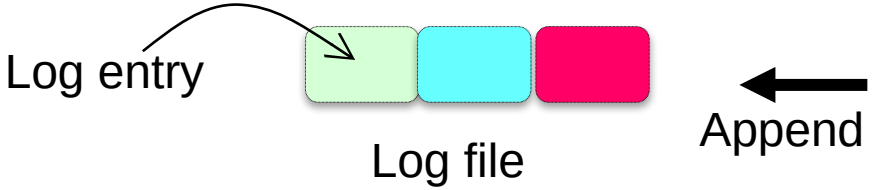
    record[a] = new_a
    record[b] = new_b
```

`log.append(commit_log).sync()`'s return is the commit point

- After it returns, the transfer's updates must be all

The whole all-or-nothing unit is usually called transaction (TX)

Crash recovery of commit log



After reboot, we need to recover the systems to a consistent state

- Based on the log entries stored in the log file

Rules

1. Travel from start to end
2. Re-apply the updates recorded in a complete log entry

Review: Pros & Cons of redo-only logging so far

Pros

- The commit is extremely efficient: only one file append operations (w/ updated data)
    - Other methods, e.g., shadow copy copies the entire file

Cons

- Wastes of disk I/O: all disk operations must happen at the commit point
- **All updates must be buffered in the memory** until the transaction commits
    - What if there is insufficient memory?
- **The log file is continuously growing** while most its updates are already flushed to the disk (unless the machine is rebooted or crashed, and we do the recovery)

Pros & Cons of redo-only logging so far

Pros

- The commit is extremely efficient: only one file append operations (w/ updated data)
    - Other methods, e.g., shadow copy copies the entire file

Cons

- Wastes of disk I/O: all disk operations must happen at the commit point
- All updates must be buffered in the memory until the transaction commits
    - What if there is insufficient memory?
- The log file is continuously growing while most its updates are already flushed to the disk

Unlike filesystem journaling, the user can commit a lot of entries in a transaction

Basic idea

We allow the transaction directly writing uncommitted values to the disk

- Before the commit point to free-up memory space & utilize disk I/O

```
transfer(bank, a, b, amt, log): // amt=10
    records = mmap(bank, ...)

    records[a] = records[a] – amt

    records[b] = records[b] + amt
```

The OS will flush the page back if out of the memory

Problem

- How to prevent a partial updates from uncommitted transactions?

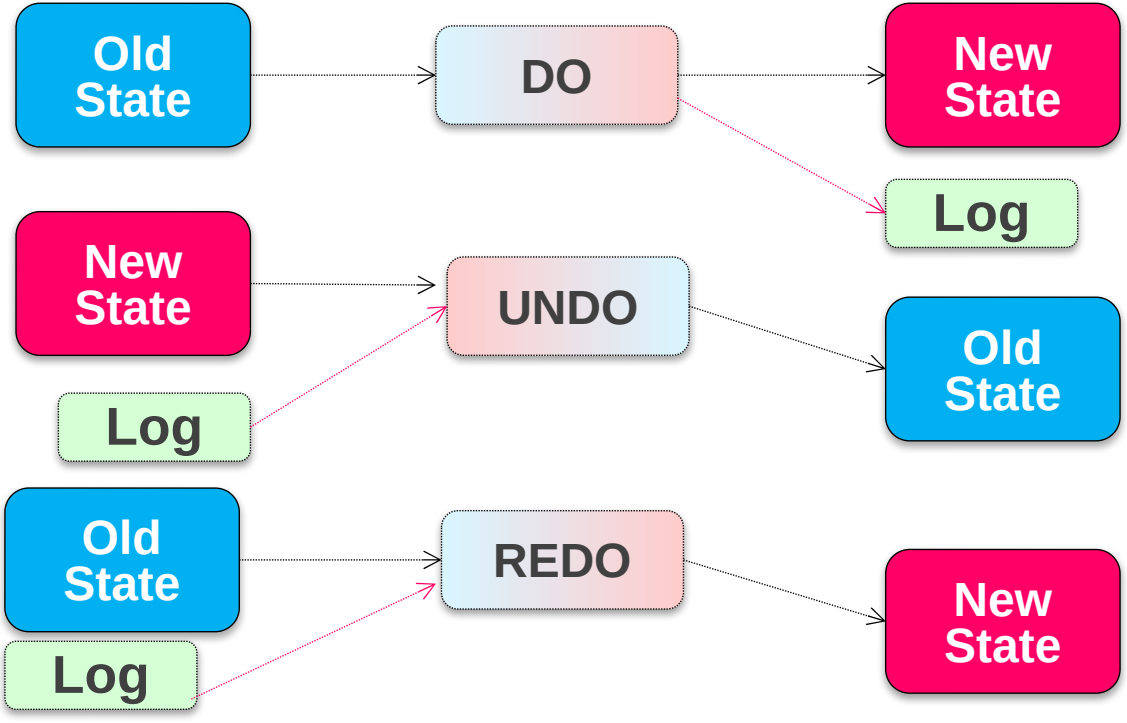
Idea: use log to **undo** updates of uncommitted transactions!

Undo logging

Keep a log of all update actions

Log

– The log can undo the (partial) updates of a DO operation



Logging w/ undo

Before updates, write an undo log record to the log file

- Should contain sufficient information to undo uncommitted transactions
- E.g., old values

```
transfer(bank, a, b, amt, log): // amt=10
    records = mmap(bank, ...)
    log.append(...).sync()
    records[a] = records[a] – amt
    log.append(...).sync()
    records[b] = records[b] + amt
```

Action (file name, offset, **old value**)

Question: do we need the redo entry?

Logging w/ undo-redo logging

Question: do we need the redo entry?

- Depends on whether we wait for records[a] to be written to the disk (e.g., sync)
- **Typically, yes:** waiting two disk syncs are slow!
  - Especially for non-logging writes: log is a fast sequential disk write

```
transfer(bank, a, b, amt, log): // amt=10
    records = mmap(bank, ...)
    log.append(...).sync()
    records[a] = records[a] – amt
    log.append(...).sync()
    records[b] = records[b] + amt

    log.append("TX {id} commit”).sync()
```

Action (file name, offset, **old & new values**)

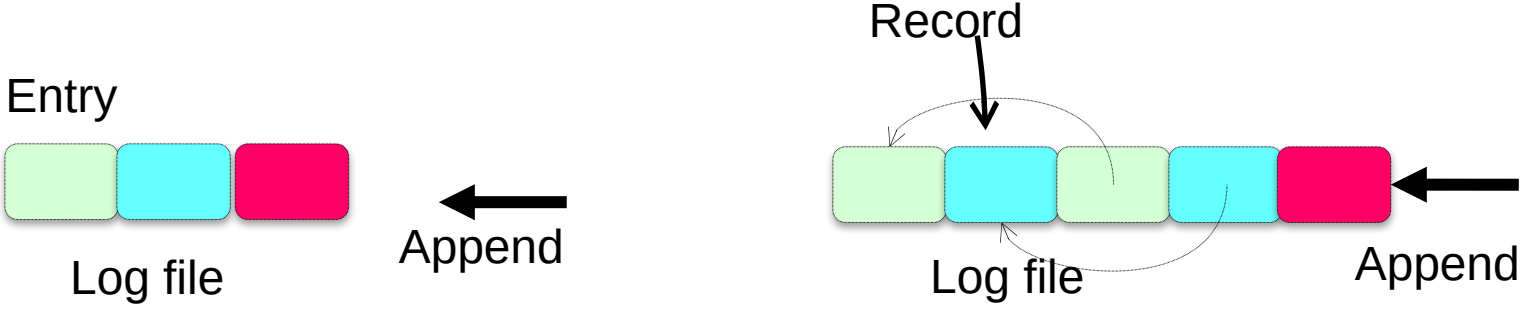
Log entry vs. log record

Redo-only logging appends log entry to the log file

- Containing all the updates of the transaction

Undo-redo logging appends log records to the log file

- Containing the updates of a single operation
- Log records from different transaction (TX) may possibly interleave
  - E.g., the OS schedules the transaction out
  - Therefore, we further need pointer to trace operations from the same TX

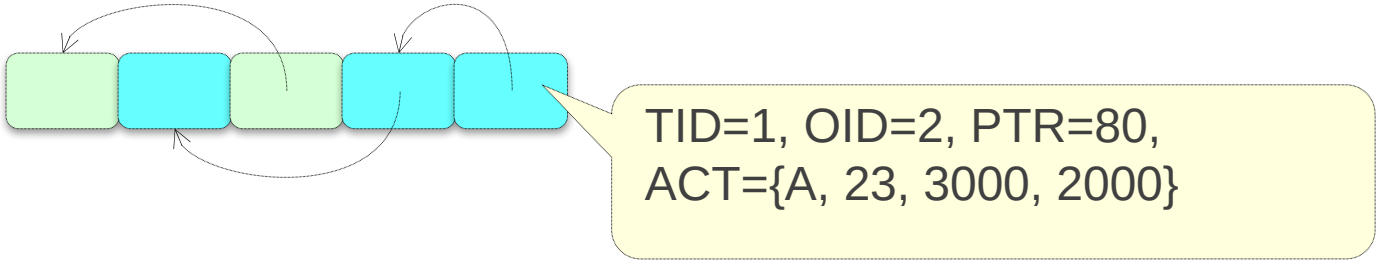


Put it all together: log record in undo-do logging

Each log record consists of

1. Transaction ID
2. Operation ID
3. Pointer to previous record in this transaction
4. Value (file name, offset, old & new value)
5. …

Log



Put it all together: logging rules

```
transfer(bank, a, b, amt, log): //
amt=10
  records = mmap(bank, ...)
  log.append(...).sync()
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  records[b] = records[b] + amt
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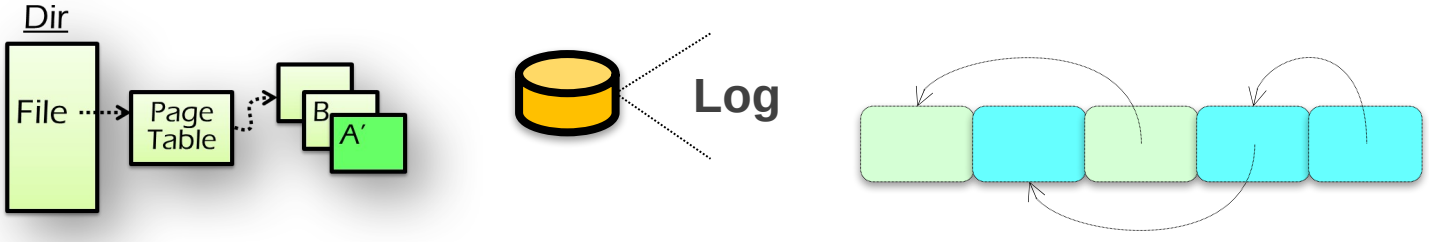
```

Write log record to disk before modifying persistent state

- (e.g., replace A’s value)
- Write Ahead Log (WAL) protocol



Put it all together: logging rules

```
transfer(bank, a, b, amt, log): //
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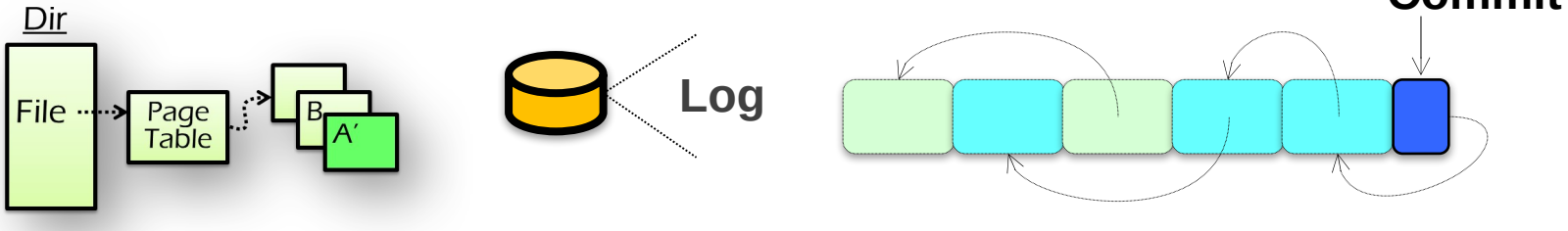
  log.append("TX {id} commit”).sync()
```

Write log record to disk before modifying persistent state

- (e.g., replace A’s value)
- Write Ahead Log (WAL) protocol

At commit point, append a commit record to the log last

- E.g., when user calls commit



Recovery rules

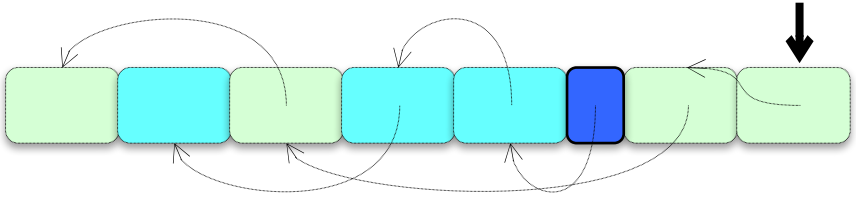
How to **recovery from crash**?

Read the log and recover states according to its content

Rules:

1. Travel from end to start

Log



Recovery rules

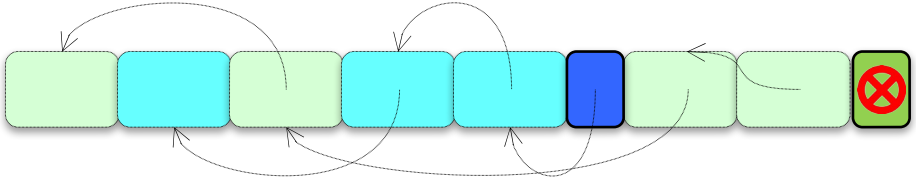
How to **recovery from crash**?

Read the log and recover states according to its content

Rules:

1. Travel from end to start
2. Mark all TX's log record w/o CMT ABORT log

Log



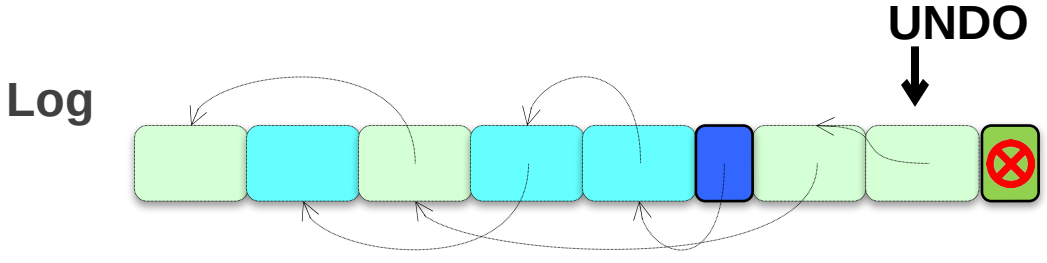
Recovery rules

How to **recovery from crash**?

Read the log and recover states according to its content

Rules:

1. Travel from end to start
2. Mark all TX's log record w/o CMT ABORT log
3. UNDO ABORT logs from end to start



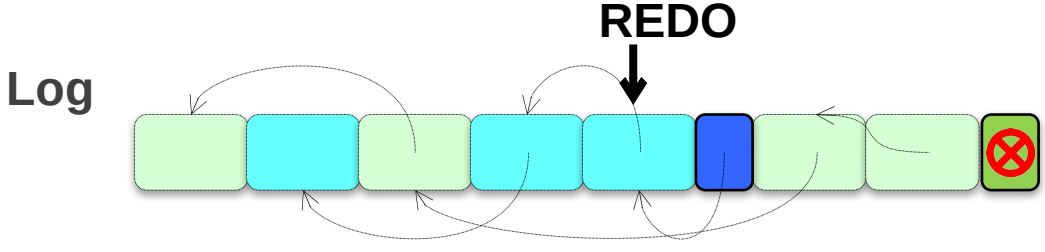
Recovery rules

How to **recovery from crash**?

Read the log and recover states according to its content

Rules:

1. Travel from end to start
2. Mark all TX's log record w/o CMT ABORT log
3. UNDO ABORT logs from end to start
4. REDO CMT logs from start to end



Problem: continuously growing of the log file

Both redo-only logging & undo-redo logging append to the log file

- The log file is continuously growing while most its updates are already flushed to the disk
- The log is only deleted if there is a single machine failure

Typically, a machine fails less frequent

- E.g., one per day

We need checkpoint the log file to reduce the log file size!

- Checkpoint: Determining which parts of the log can be discarded, then discarded them

Checkpoint the log

Naïve solution

- Run the recovery process. If it is done, then we can discard all the log file
- Problem: too slow

Observation

- For redo logging, we only need to flush the page caches so we can discard all the logs of committed TXs
- For undo logging, we only need to wait for TXs to finish to discard all its log entries

How to checkpoint? (For both undo + redo logging)

Basic approach

1. Wait till no TXs are in progress
2. Flush the page cache
3. Discard all the logs

Question

- What if a TX is doing a long time? Can we allow ongoing TXs?
- We need to reserve the log for ongoing TXs !

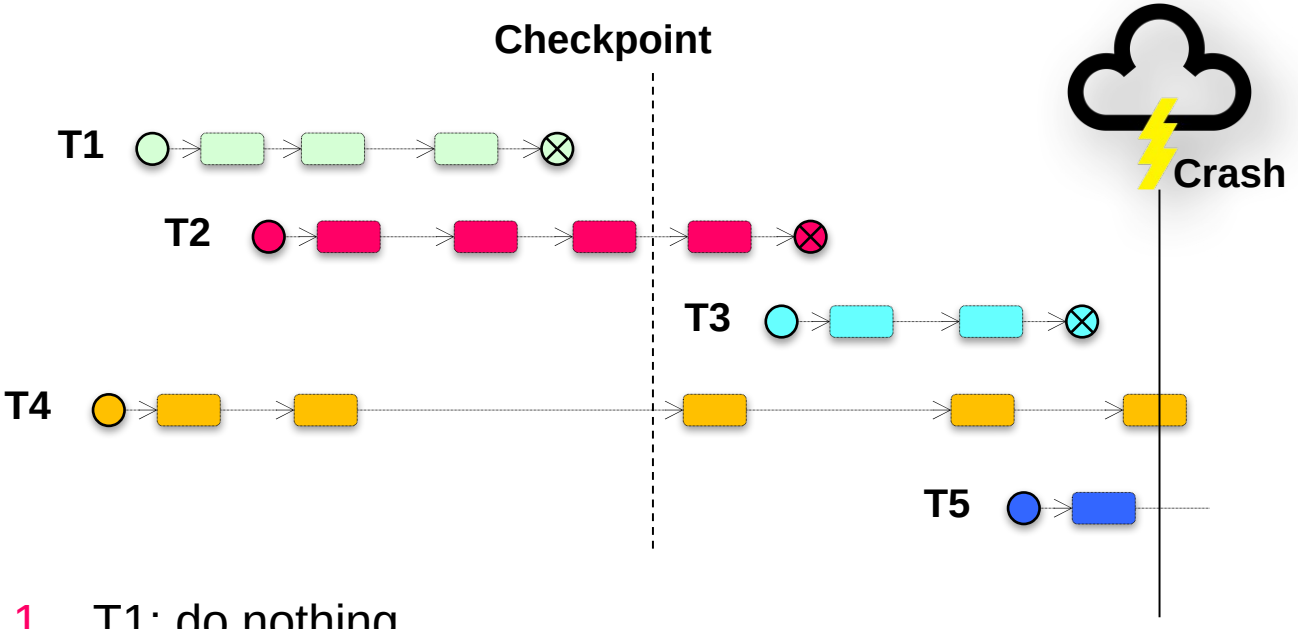
How to checkpoint?

How to checkpoint?

actions

1. Wait till no ~~transactions~~ are in progress
2. Write a **CKPT** record to log
    - Contains a list of all transaction in process and their logs
3. Flush the page cache
4. Discard all the log records except the CKPT record

Recovery with checkpoint



1. T1: do nothing
2. T2: redo its update based on the log in its checkpoint
3. T3: redo its updates based on the log entries
4. T4: undo its updates based on the log in both CKP & log entries
5. T5: undo its updates based on the log entries

Undo-redo logging vs. redo-only logging

Question:

- Which one is faster during execution?
- Which one is faster during recovery?

Redo-only logging

- Less disk operations compared with undo-redo logging
- Only need one scan of the entire log file

Redo-only logging is typically preferred except for TXs with large in-memory states

UNDO-only Logging

Logging rules

- Append **UNDO** log record **before** flushing state modification
- State modification must be flushed before transaction committed
    - w/o REDO

Rarely used

- Much slower than UNDO-REDO logging during **execution**
- Though the **recovery** speed is faster

Summary & durability

Systematic methods to support all-or-nothing atomicity

- Shadow copy (Single-file updates)
- Journaling (Filesystem API)

Logging (General-purpose approaches)

- REDO-only logging (commit logging)
- UNDO-REDO logging (write-ahead logging)
- UNDO-only logging

Durability: Committed Action’s data on durable storage

- Logging is also a method to ensure durability

Before-or-after atomicity

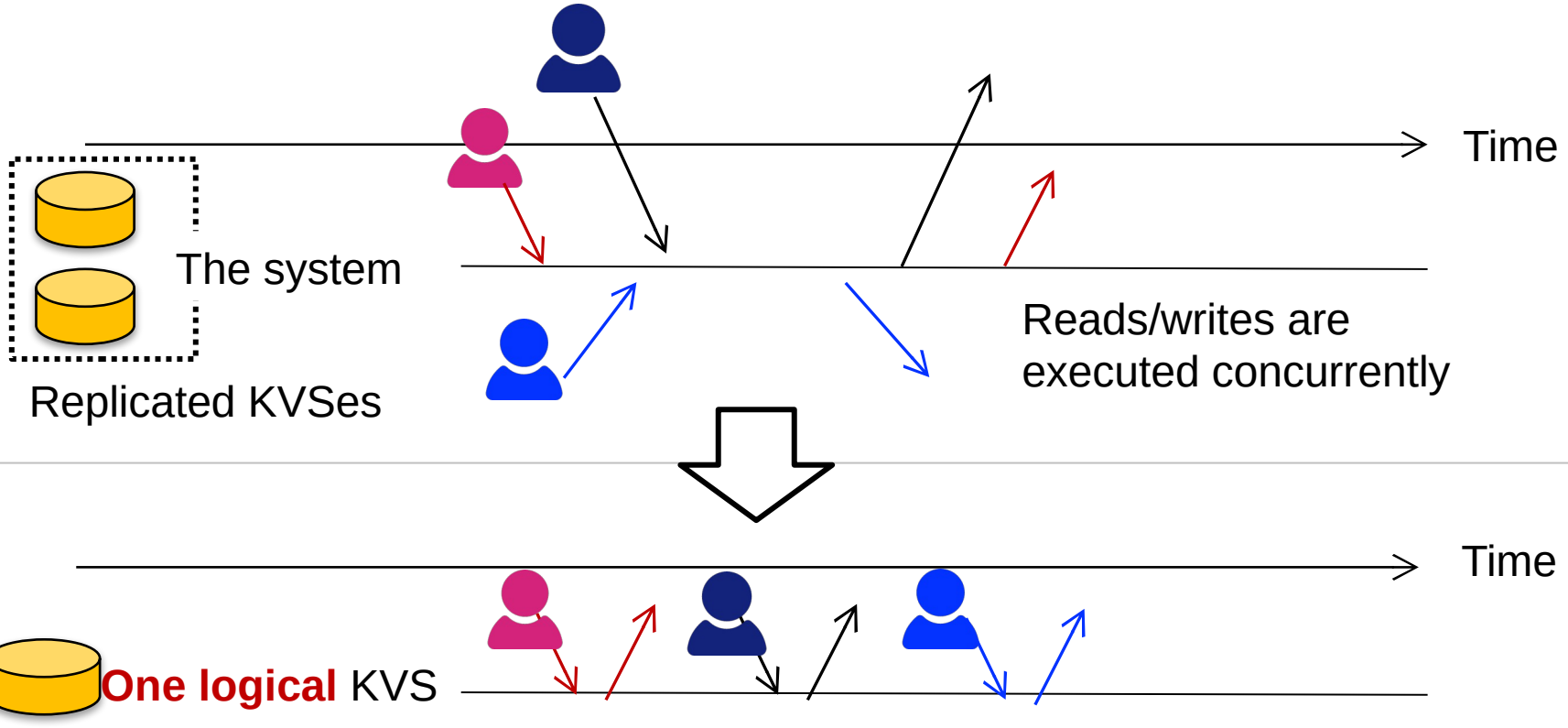
We will evolve from single-threaded to multi-threaded setting

What is a strong consistency model

It's easy for users to reason about correctness assuming

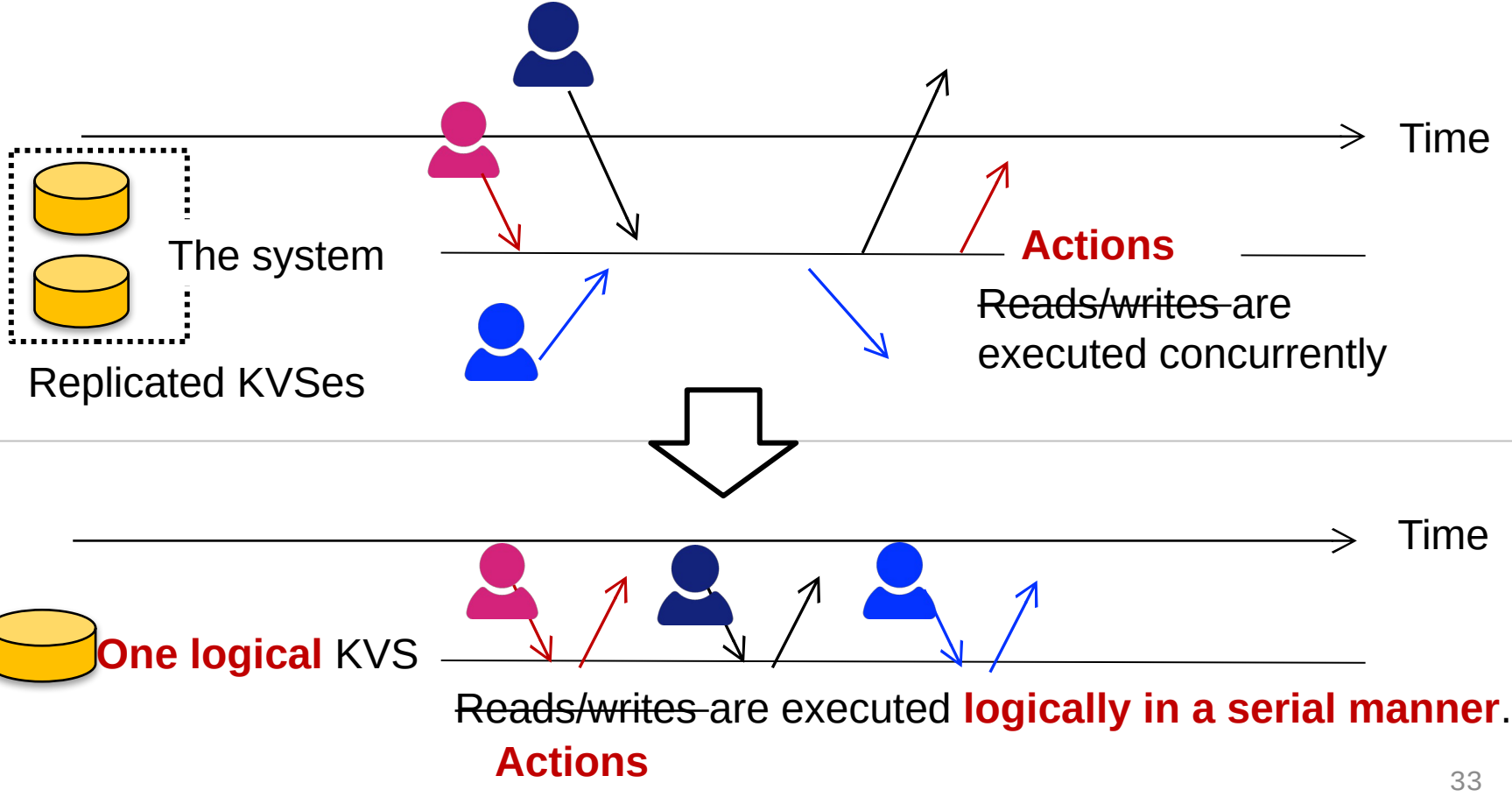
- Everything has only one-copy
- **The overall behavior is equivalent to some serial behavior**
- The operations that need to be executed in an atomic unit (usually called operations belonging to a transaction) are executed on a machine that happens completely or not at all (all-or-nothing atomicity)

Review: serial execution of reads/writes



Reads/writes are executed **logically in a serial manner**.

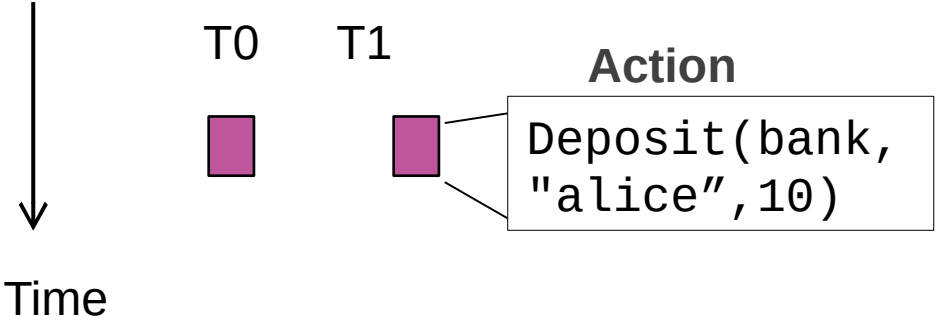
One step further: serial execution of actions



Motivating example

Example: consider **two** threads **access the same account concurrently**

- We have a in-memory array to store all the accounts w/o losing generality



Action implementation

```
Deposit(bank, acct, amt):
    bank[acct] += amt
```

Question: What are the expected behavior?

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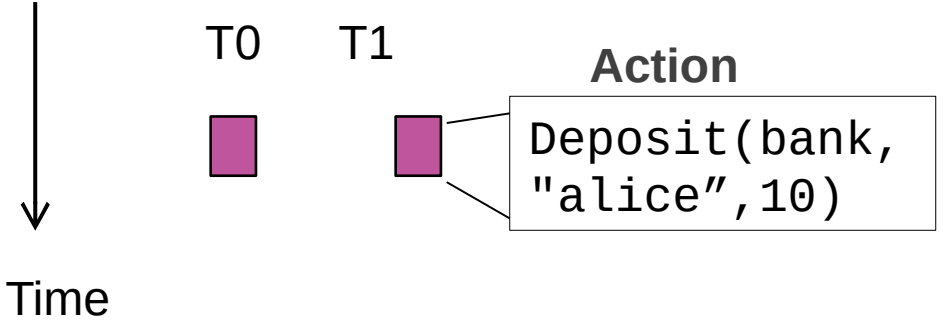

Action

```
Deposit(bank,
"alice”,10)
```

Action implementation

```
Deposit(bank, acct,
amt):
    bank[acct] += amt
```

Question: What are the expected behavior?

Atomicity of the + operator

Example: consider **two** threads **access the same account concurrently**

- Even a simple + operator is **non-atomic**

Why would this happen?

- The `deposit` function is **not atomic, even assuming each mov is linearizable!**
  - CPU can only guarantee the atomicity of one memory op, but it has two

```
Deposit(bank, acct,
amt):
    bank[acct] += amt
```

Developer's written code

```
mov     acct, %eax
add     $amt, %eax
mov     %eax, acct
```

Compiler's generated code

Atomicity of the + operator

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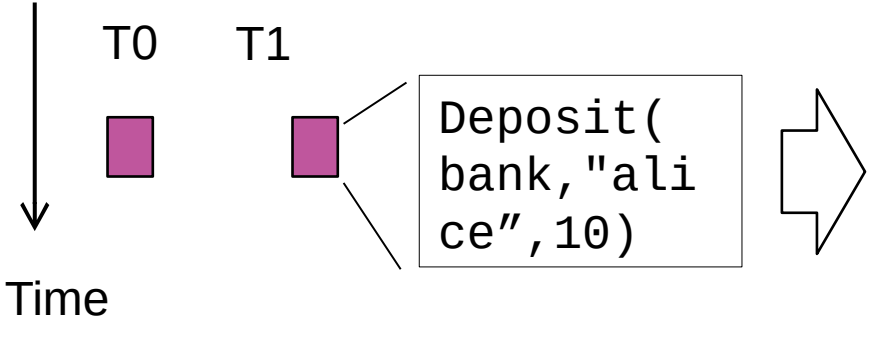

Thread 0	Thread 1	Bank[Alice]
		0

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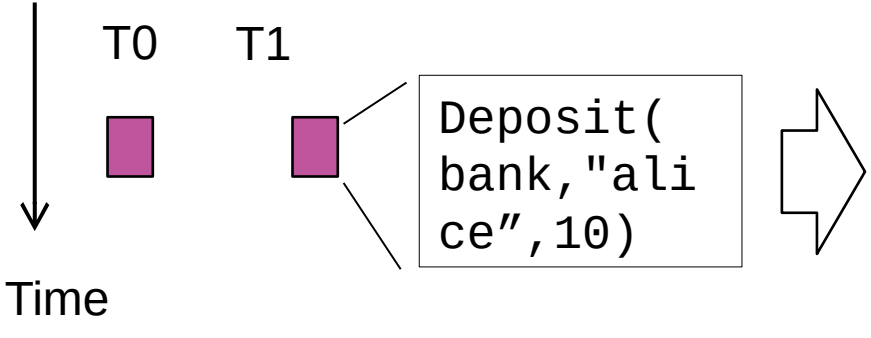

Thread 0	Thread 1	Bank[Alice]
		0
Read acct	←	0

Atomicity of the + operator

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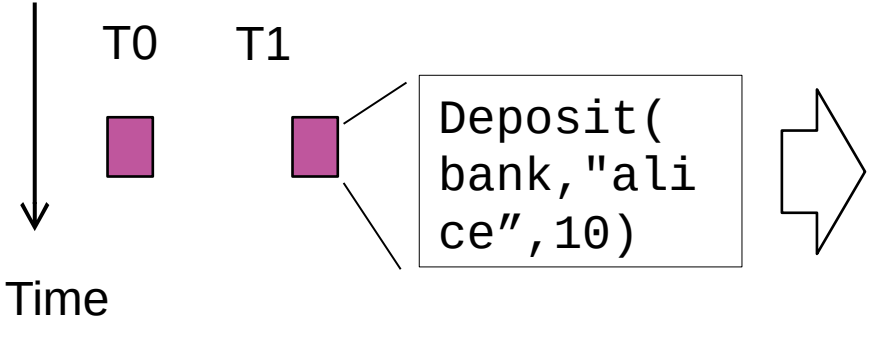

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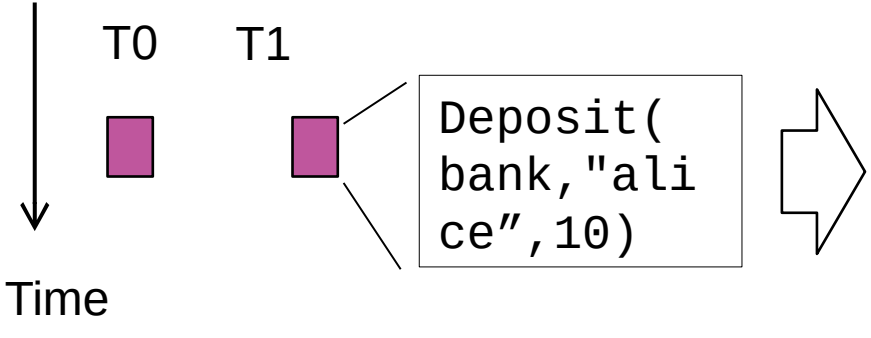

Thread 0	Thread 1	Bank[Alice]
		0
Read acct	←	0
	Read acct ←	0
Increase		0

Atomicity of the + operator

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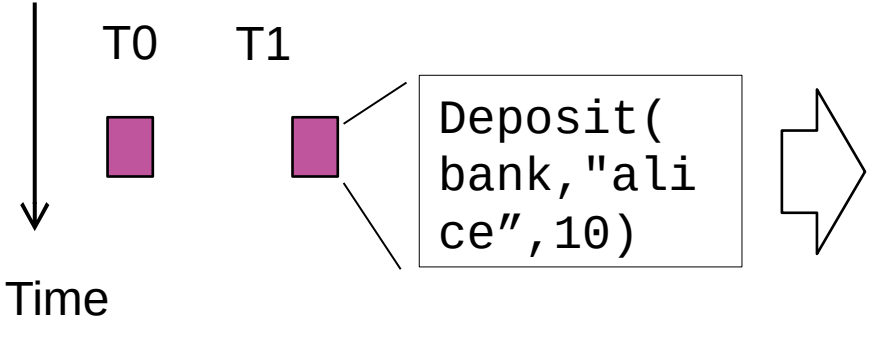

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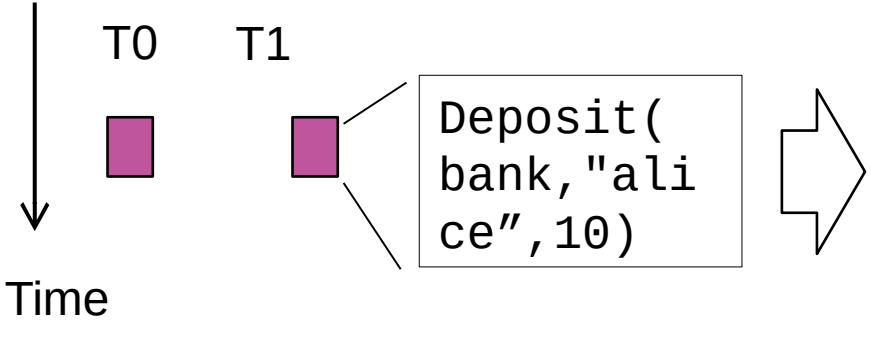

Thread 0	Thread 1	Bank[Alice]
		0
Read acct	←	0
	Read acct ←	0
Increase		0
	Increase	0
Write acct	→	10

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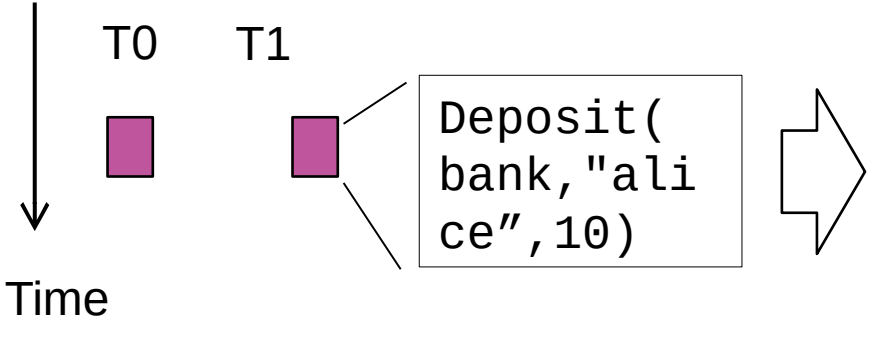
```

Compiler's generated code



Thread 0	Thread 1	Bank[Alice]
		0
Read acct	←	0
	Read acct ←	0
Increase		0
	Increase	0
Write acct	→	10
	Write acct →	**10**

The **race condition** problem

When two or more threads access shared data and at least one is write

Timing dependent error involving shared state

- i.e., whether the scheduling will cause reading a non-atomic update state

Thread 0	Thread 1		Bank[Alice]
			0
Read acct		←	0
	Read acct	←	0
Increase			0
	Increase		0
Write acct		→	10
	Write acct	→	**10**

Thread 0	Thread 1		Bank[Alice]
			0
Read acct		←	0
Increase			0
		→	10
Write acct	Read acct	←	10
	Increase		10
	Write acct	→	**20**

Race condition is hard to control

Must make sure all possible schedules are safe

- Number of possible schedules permutations is huge
- Bad schedules that will and will not work sometimes

They are intermittent

- Small timing changes between invocations might result in different behavior which can hide bug (e.g., Therac-25)
- Also known as **Heisenbugs** (Heisenberg uncertainty)
    - Possible system solution-1: DMT (Deterministic Multi-Threading)
    - Possible system solution-2: Record and Replay
    - Both are hard in either correctness or cost, or both

Race condition is common (benign case)

Real-world computing systems embrace concurrency

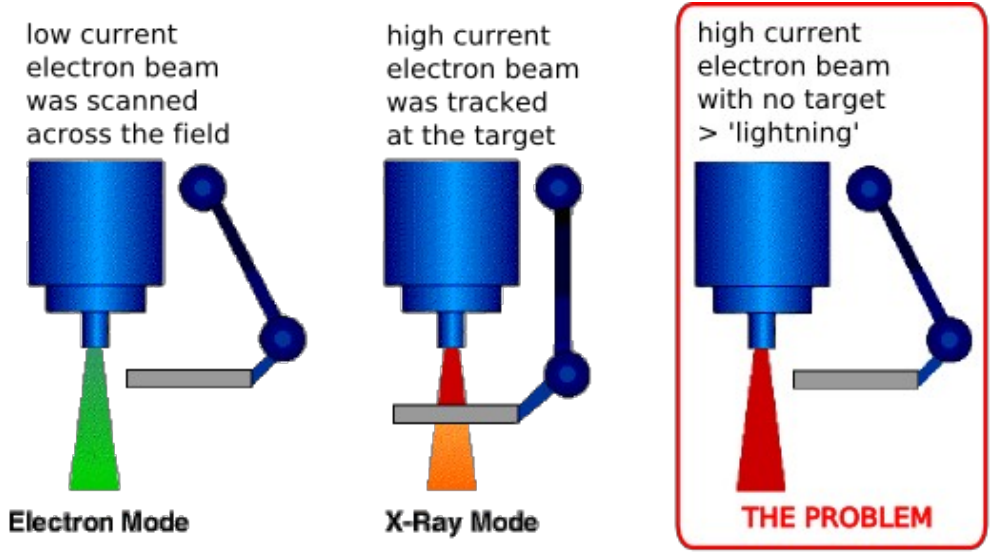
- E.g., embrace the design of distributed systems

Bad: race condition brings unsatisfactory to the customers

- E.g., the comment system in 知

Show 5 comments;
But only 3 presented on the app

Race condition may be dangerous (e.g., in Therac-25)



tray including the target, a flattening filter, the collimator jaws and an ion chamber was moved OUT for "electron" mode, and IN for "photon" mode.

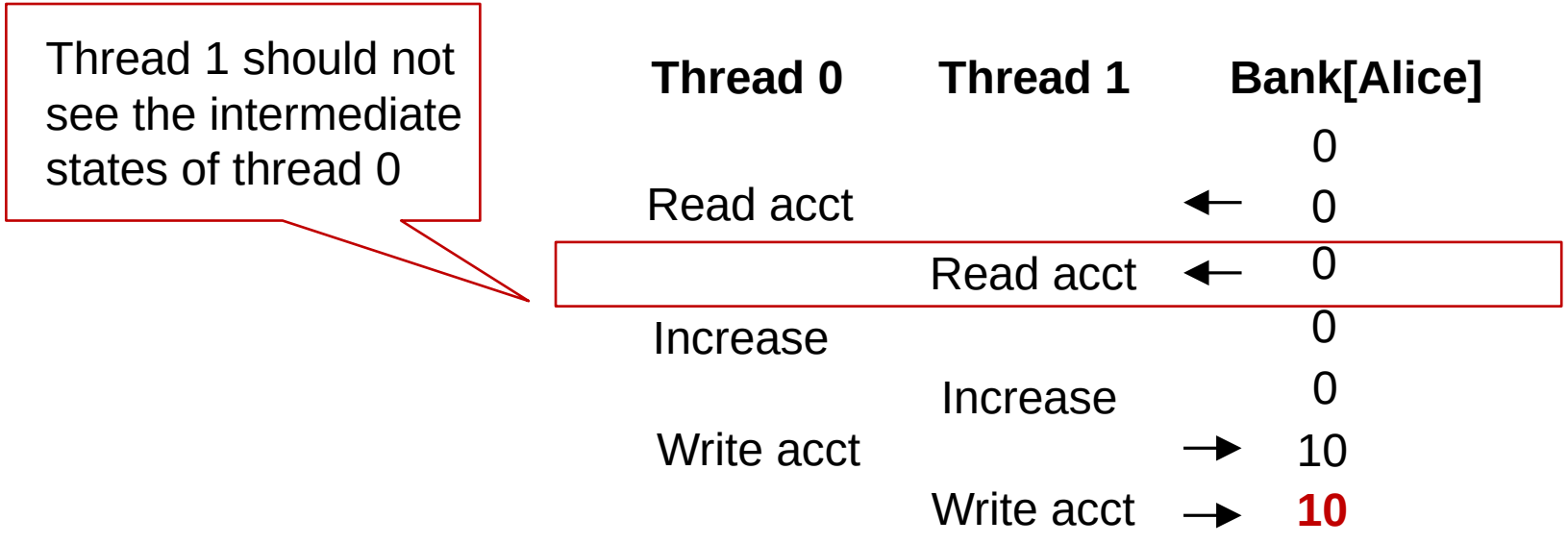
The equipment control task did not properly synchronize with the operator interface task, so that race conditions occurred if the operator changed the setup too quickly. In three cases, the injured patients later died as a result of the overdose.

Before-or-After Atomicity

Goal: **before-or-after atomicity**

To prevent hazard produced by race condition, we need a group of reads/writes to be atomic

- E.g., cannot see/overwrites the **intermediate** states of a concurrent action



Goal: **before-or-after atomicity (a.k.a, Isolation)**

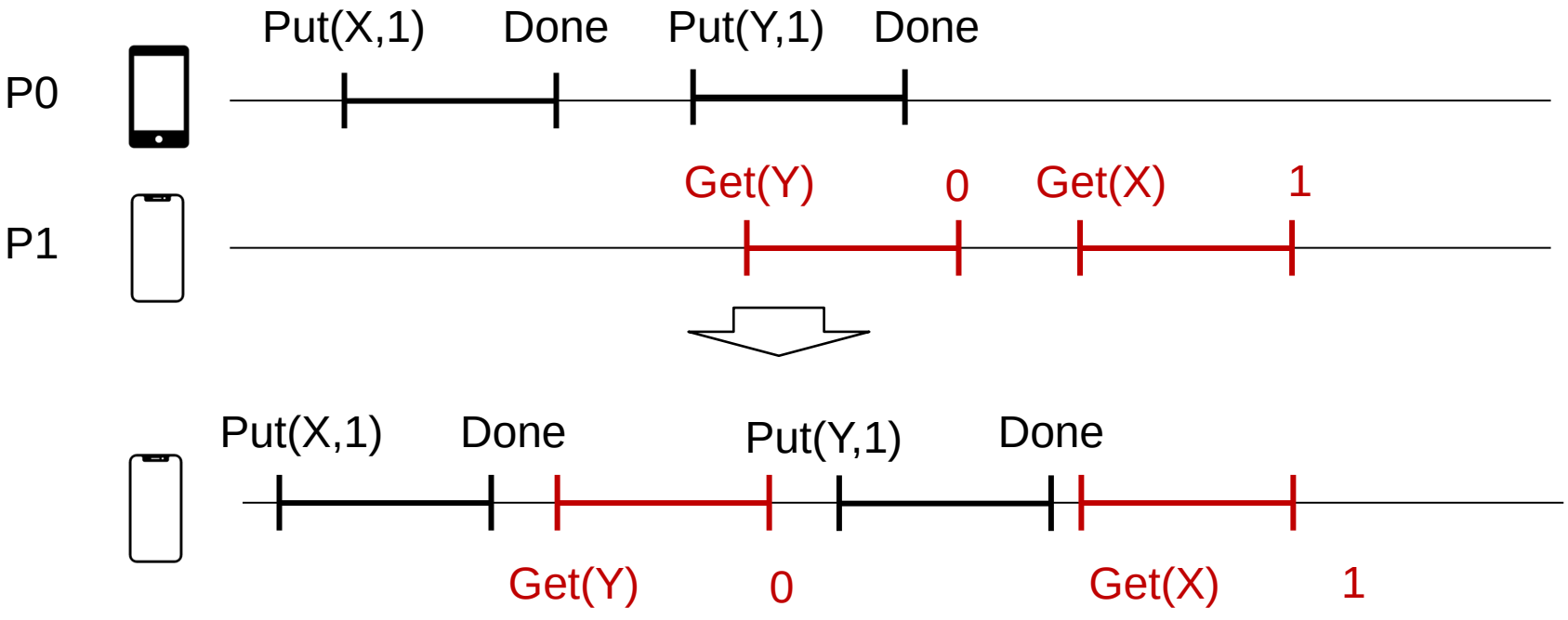
To prevent hazard produced by race condition, we need a group of reads/writes to be atomic

- E.g., cannot see/overwrites the **intermediate** states of a concurrent action
- A concurrent action may have multiple linearizable reads/writes

Before or after atomicity

Concurrent actions have the **before-or-after property** if their effect from the point of view of their invokers is as **if the actions occurred either completely before or completely after one another**

Before-or-after vs. Linearizability



The above schedule is allowed in Linearizability, but not before-or-after atomicity

Use locking to achieve before-or-after

Locks: a data structure that allows only one CPU acquire at a given time

- Programs can **acquire** and **release** the lock
- If the acquisition fails, then the CPU will wait until it is succeed
- Example: `pthread_mutex`

Implementing the locks efficiently is a broad topic

- And is non-trivial: out of the scope of this lecture

Use locking to achieve before-or-after: **global lock**

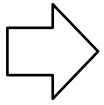
Locks: a data structure that allows only one CPU acquire at a given time

- Programs can **acquire** and **release** the lock
- If the acquisition fails, then the CPU will wait until it is succeed
- Example: `pthread_mutex`

Global lock:

- The action must acquire the global lock before executing, and release it after it commits

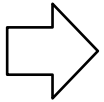
```
Deposit(bank, acct,
amt):
    bank[acct] += amt
```



```
Deposit(bank, lock, acct,
amt):
    acquire(lock)
    bank[acct] += amt
    release(lock)
```

Use locking to achieve before-or-after: **global lock**

```
Deposit(bank, acct,
amt):
    bank[acct] += amt
```



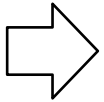
```
Deposit(bank, lock, acct,
amt):
    acquire(lock)
    bank[acct] += amt
    release(lock)
```

Thread 0	Thread 1		Bank[Alice]
			0
Read acct		←	0
	Read acct	←	0
Increase			0
	Increase		0
Write acct		→	10
	Write acct	→	**10**

Thread 0	Thread 1	Bank[Alice]
		0

Use locking to achieve before-or-after: **global lock**

```
Deposit(bank, acct,
amt):
    bank[acct] += amt
```



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Deposit(bank, lock, acct,
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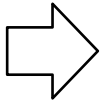
    acquire(lock)
    bank[acct] += amt
    release(lock)
```

Thread 0	Thread 1		Bank[Alice]
			0
Read acct		←	0
	Read acct	←	0
Increase			0
	Increase		0
Write acct		→	10
	Write acct	→	**10**

Thread 0	Thread 1	Bank[Alice]
		0
Acquire(lock)		0

Use locking to achieve before-or-after: **global lock**

```
Deposit(bank, acct,
amt):
    bank[acct] += amt
```



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Deposit(bank, lock, acct,
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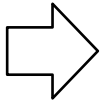
    acquire(lock)
    bank[acct] += amt
    release(lock)
```

Thread 0	Thread 1		Bank[Alice]
			0
Read acct		←	0
	Read acct	←	0
Increase			0
	Increase		0
Write acct		→	10
	Write acct	→	**10**

Thread 0	Thread 1		Bank[Alice]
			0
Acquire(lock)			0
Read acct		←	0

Use locking to achieve before-or-after: **global lock**

```
Deposit(bank, acct,
amt):
    bank[acct] += amt
```



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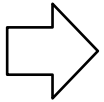
Deposit(bank, lock, acct,
amt):
    acquire(lock)
    bank[acct] += amt
    release(lock)
```

Thread 0	Thread 1		Bank[Alice]
			0
Read acct		←	0
	Read acct	←	0
Increase			0
	Increase		0
Write acct		→	10
	Write acct	→	**10**

Thread 0	Thread 1		Bank[Alice]
			0
Acquire(lock)			0
Read acct		←	0
	Acquire(lock)		0

Use locking to achieve before-or-after: **global lock**

```
Deposit(bank, acct,
amt):
    bank[acct] += amt
```



```
Deposit(bank, lock, acct,
amt):
    acquire(lock)
    bank[acct] += amt
    release(lock)
```

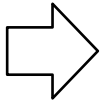
Thread 0	Thread 1	Bank[Alice]
		0
Read acct ←		0
	Read acct ←	0
Increase		0
	Increase	0
Write acct →		10
	Write acct →	**10**

Thread 0	Thread 1	Bank[Alice]
		0
Acquire(lock)		0
Read acct ←		0
	Acquire(lock)	0
	Read acct ←	0

Can this happen?

Use locking to achieve before-or-after: **global lock**

```
Deposit(bank, acct,
amt):
    bank[acct] += amt
```



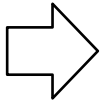
```
Deposit(bank, lock, acct,
amt):
    acquire(lock)
    bank[acct] += amt
    release(lock)
```

Thread 0	Thread 1	Bank[Alice]
		0
Read acct ←		0
	Read acct ←	0
Increase		0
	Increase	0
Write acct →		10
	Write acct →	**10**

Thread 0	Thread 1	Bank[Alice]
		0
Acquire(lock)		0
Read acct	←	0
	Acquire(lock)	0

Use locking to achieve before-or-after: **global lock**

```
Deposit(bank, acct,
amt):
    bank[acct] += amt
```



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    acquire(lock)
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    release(lock)
```

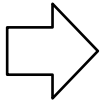
Thread 0	Thread 1		Bank[Alice]
			0
Read acct		←	0
	Read acct	←	0
Increase			0
	Increase		0
Write acct		→	10
	Write acct	→	**10**

Thread 0	Thread 1		Bank[Alice]
			0
Acquire(lock)			0
Read acct		←	0
	Acquire(lock)		0
Increase	Acquire(lock)		0

Thread is stuck at the acquiring the lock

Use locking to achieve before-or-after: **global lock**

```
Deposit(bank, acct,
amt):
    bank[acct] += amt
```



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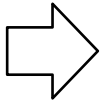
Deposit(bank, lock, acct,
amt):
    acquire(lock)
    bank[acct] += amt
    release(lock)
```

Thread 0	Thread 1	Bank[Alice]
		0
Read acct ←		0
	Read acct ←	0
Increase		0
	Increase	0
Write acct →		10
	Write acct →	**10**

Thread 0	Thread 1	Bank[Alice]
		0
Acquire(lock)		0
Read acct ←		0
	Acquire(lock)	0
Increase	Acquire(lock)	0
Write back →	Acquire(lock)	10

Use locking to achieve before-or-after: **global lock**

```
Deposit(bank, acct,
amt):
    bank[acct] += amt
```



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Deposit(bank, lock, acct,
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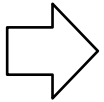
    release(lock)
```

Thread 0	Thread 1	Bank[Alice]
		0
Read acct ←		0
	Read acct ←	0
Increase		0
	Increase	0
Write acct →		10
	Write acct →	**10**

Thread 0	Thread 1	Bank[Alice]
		0
Acquire(lock)		0
Read acct ←		0
	Acquire(lock)	0
Increase	Acquire(lock)	0
Write back →	Acquire(lock)	10
Release(lock)	Acquire(lock)	10

Use locking to achieve before-or-after: **global lock**

```
Deposit(bank, acct,
amt):
    bank[acct] += amt
```



```
Deposit(bank, lock, acct,
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    acquire(lock)
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    release(lock)
```

Thread 0	Thread 1	Bank[Alice]
		0
Read acct ←		0
	Read acct ←	0
Increase		0
	Increase	0
Write acct →		10
	Write acct →	**10**

Thread 0	Thread 1	Bank[Alice]
		0
Acquire(lock)		0
Read acct ←		0
	Acquire(lock)	0
Increase	Acquire(lock)	0
Write back →	Acquire(lock)	10
Release(lock)	Acquire(lock)	10
	Increase	10

Use locking to achieve before-or-after: **global lock**

```
Deposit(bank, acct,
amt):
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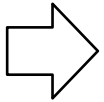
```



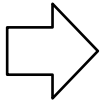
```
Deposit(bank, lock, acct,
amt):
    acquire(lock)
    bank[acct] += amt
    release(lock)
```

Thread 0	Thread 1		Bank[Alice]
			0
Read acct		←	0
	Read acct	←	0
Increase			0
	Increase		0
Write acct		→	10
	Write acct	→	**10**

Thread 0	Thread 1		Bank[Alice]
			0
Acquire(lock)			0
Read acct		←	0
	Acquire(lock)		0
Increase	Acquire(lock)		0
Write back	Acquire(lock)	→	10
Release(lock)	Acquire(lock)		10
	Increase		10
	Write back	→	20

Use locking to achieve before-or-after: **global lock**

```
Deposit(bank, acct,
amt):
    bank[acct] += amt
```



```
Deposit(bank, lock, acct,
amt):
    acquire(lock)
    bank[acct] += amt
    release(lock)
```

Thread 0	Thread 1		Bank[Alice]
			0
Read acct		←	0
	Read acct	←	0
Increase			0
	Increase		0
Write acct		→	10
	Write acct	→	**10**

Thread 0	Thread 1		Bank[Alice]
			0
Acquire(lock)			0
Read acct		←	0
	Acquire(lock)		0
Increase	Acquire(lock)		0
Write back	Acquire(lock)	→	10
Release(lock)	Acquire(lock)		10
	Increase		10
	Write back	→	20
	Release(lock)		20

Use locking to achieve before-or-after: **global lock**

Locks: a data structure that allows only one CPU acquire at a given time

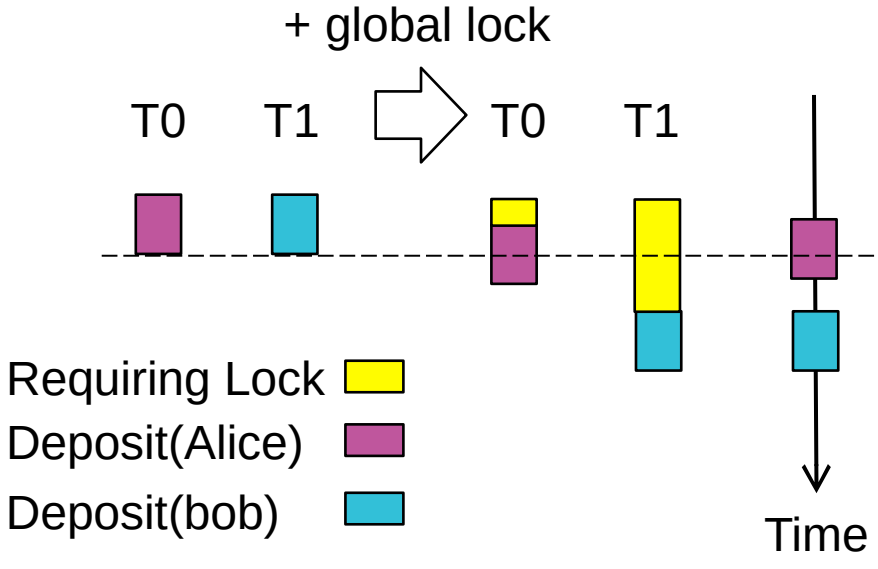
- Programs can **acquire** and **release** the lock

Global lock:

- The action must acquire the global lock before executing, and release it after it commits

Drawback: too coarse-grained

- Only allow one action to run at a time
- Even they don't read/write each other



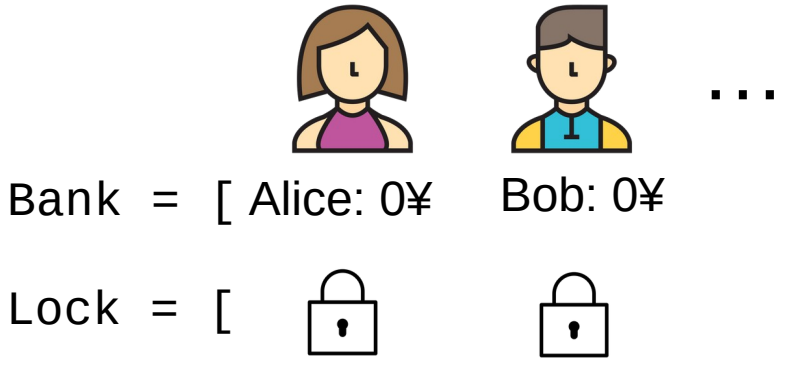
Use locking to achieve before-or-after: **fine-grained locking**

Fine-grained locking:

- Each shared data has one lock
- E.g., a lock for Alice & a lock for Bob

Locking rule:

- The action must acquire the shared data's lock before access it, and releases it after the data access finishes




```
Deposit(bank, lock, acct,
amt):
    acquire(lock)
    bank[acct] += amt
    release(lock)
```

```
Deposit(bank, lock, acct,
amt):
    acquire(lock[acct])
    bank[acct] += amt
    release(lock[acct])
```

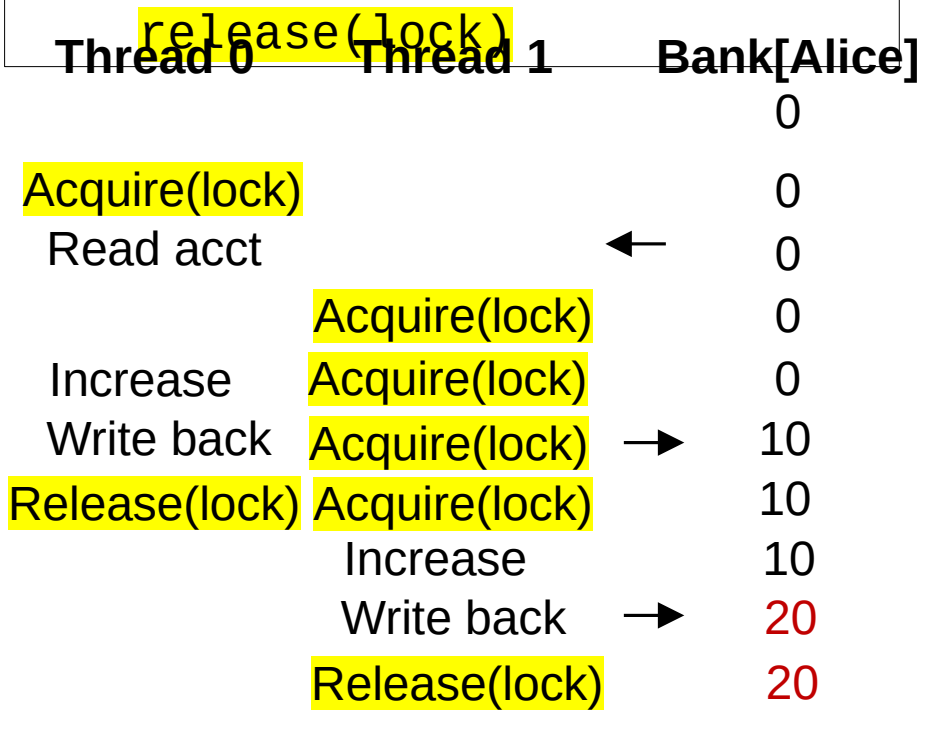
Use locking to achieve before-or-after: **fine-grained locking**

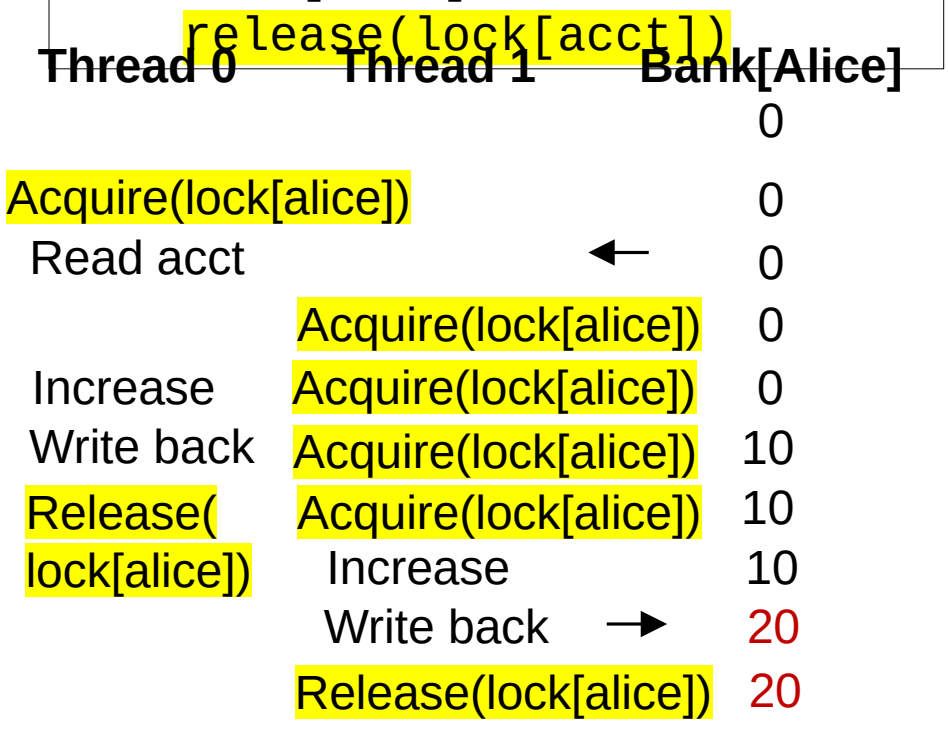
Global

```
Deposit(bank, lock, acct,
amt):
    acquire(lock)
    bank[acct] += amt
    release(lock)
```

Fine-grained

```
Deposit(bank, lock, acct,
amt):
    acquire(lock[acct])
    bank[acct] += amt
    release(lock[acct])
```

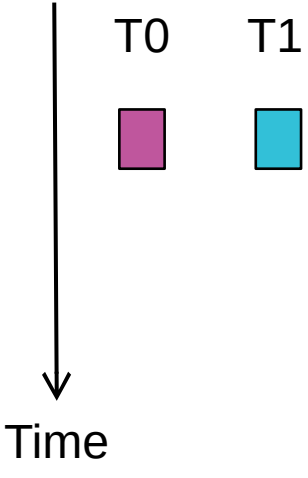




Use locking to achieve before-or-after: **fine-grained locking**

Fine-grained locking allows more concurrency

- If the deposits operate on different accounts, they can run concurrently



Thread 0	Thread 1	Bank[Alice]	Bank[Bob]
Acquire(lock[alice])	Acquire(lock[bob])	0	0
Read acct	Read acct	0	0
Increase	Increase	0	0
Write back	Write back	10	10
Release(lock[alice])	Release(lock[bob])	10	10

Deposit(Alice)

Deposit(bob)

Two deposits can run concurrently!

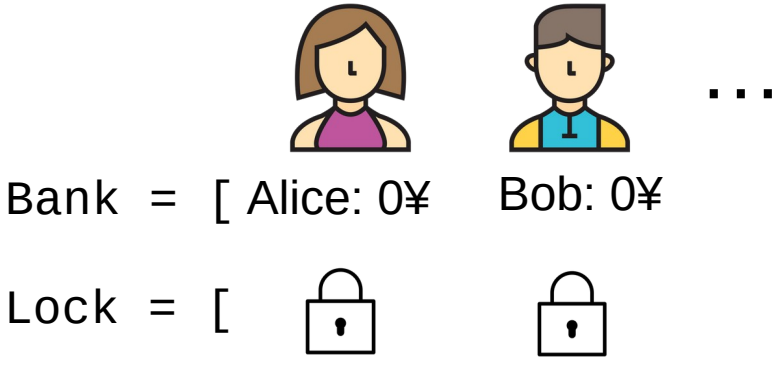
Use locking to achieve before-or-after: **fine-grained locking**

Fine-grained locking:

- Each data record has one lock
- E.g., a lock for Alice & a lock for Bob

Lock acquire rule:

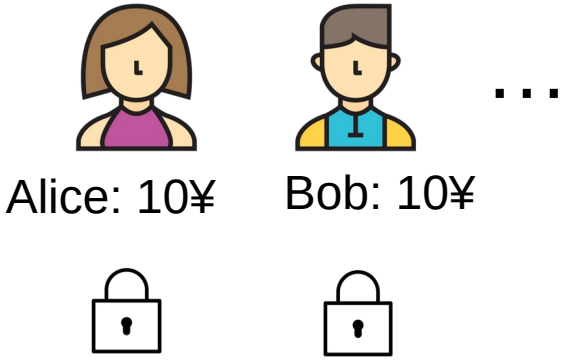
- The action must acquire the account lock before access it, and releases it after the data access finishes



Question: can fine-grained locking avoids **any** the race conditions?

More example: multiple records

Transfer + Audit for the bank application




```
Transfer(bank, locks, a, b,
amt):
    Acquire(lock[b])
    bank[b] += amt
    Release(lock[b])
    Acquire(lock[a])
    bank[a] -= amt
    Release(lock[a])
```

```
Audit(bank):
    sum = 0
    for acct in bank:

Acquire(locks[acct])
        sum += bank[acct]

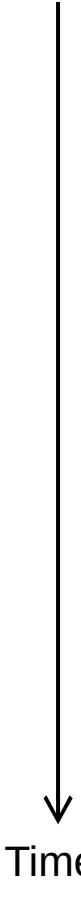
Release(locks[acct])
```

Question: what is the ideal output of Audit?

Accessing multiple records

`Transfer (alice, bob, 10)` `Audit()`

Thread 0 (Transfer)	Thread 1 (Audit)	Bank[Alice]	Bank[bob]	Sum
		10	10	0



Accessing multiple records

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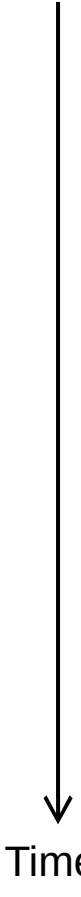
Thread 0 (Transfer)	Thread 1 (Audit)	Bank[Alice]	Bank[bob]	Sum
		10	10	0
Acquire(lock[b])	Acquire(lock[b])	10	10	0



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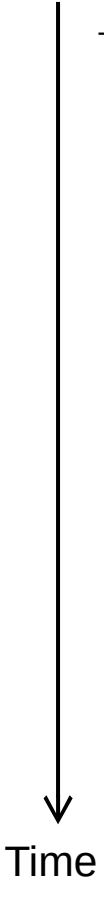

Accessing multiple records

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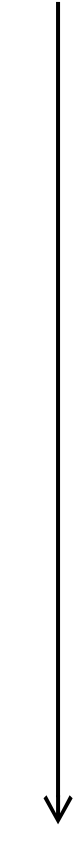
		10	10	0
Acquire(lock[b])	Acquire(lock[b])	10	10	0
Read(b) = 10	Acquire(lock[b])	10	10	0
Write(b) = 20	Acquire(lock[b])	10	**20**	0



Accessing multiple records

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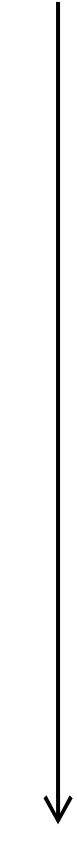
Read(b) = 10	Acquire(lock[b])	10	10	0
Write(b) = 20	Acquire(lock[b])	10	**20**	0
Release(lock[b])	Acquire(lock[b])	10	20	0



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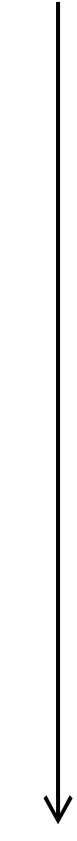
Release(lock[b])	Acquire(lock[b])	10	20	0
	Read(b) = 20	10	20	20



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Read(b) = 10	Acquire(lock[b])	10	10	0
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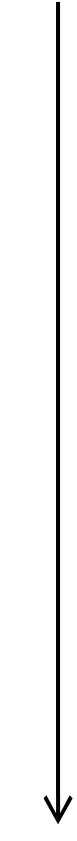
Release(lock[b])	Acquire(lock[b])	10	20	0
	Read(b) = 20	10	20	20
	Release(lock[b])	10	20	20

Time

Accessing multiple records

`Transfer (alice, bob, 10)` `Audit()`

Thread 0 (Transfer)	Thread 1 (Audit)	Bank[Alice]	Bank[bob]	Sum
		10	10	0
Acquire(lock[b])	Acquire(lock[b])	10	10	0
Read(b) = 10	Acquire(lock[b])	10	10	0
Write(b) = 20	Acquire(lock[b])	10	**20**	0
Release(lock[b])	Acquire(lock[b])	10	20	0
	Read(b) = 20	10	20	20
	Release(lock[b])	10	20	20
	Acquire(lock[a])	10	20	20



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Write(b) = 20	Acquire(lock[b])	10	**20**	0
Release(lock[b])	Acquire(lock[b])	10	20	0
	Read(b) = 20	10	20	20
	Release(lock[b])	10	20	20
	Acquire(lock[a])	10	20	20
	Read(a) = 10	10	20	30

Time

Accessing multiple records

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Read(b) = 10	Acquire(lock[b])	10	10	0
Write(b) = 20	Acquire(lock[b])	10	**20**	0
Release(lock[b])	Acquire(lock[b])	10	20	0
	Read(b) = 20	10	20	20
	Release(lock[b])	10	20	20
	Acquire(lock[a])	10	20	20
	Read(a) = 10	10	20	30
	Release(lock[a])	10	20	30

Time

Accessing multiple records

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Read(b) = 10	Acquire(lock[b])	10	10	0
Write(b) = 20	Acquire(lock[b])	10	**20**	0
Release(lock[b])	Acquire(lock[b])	10	20	0
	Read(b) = 20	10	20	20
	Release(lock[b])	10	20	20
	Acquire(lock[a])	10	20	20
	Read(a) = 10	10	20	30
	Release(lock[a])	10	20	30
Acquire(lock[a])		10	20	30

Time

Accessing multiple records

`Transfer (alice, bob, 10)` `Audit()`

Thread 0 (Transfer)	Thread 1 (Audit)	Bank[Alice]	Bank[bob]	Sum
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Acquire(lock[b])	Acquire(lock[b])	10	10	0
Read(b) = 10	Acquire(lock[b])	10	10	0
Write(b) = 20	Acquire(lock[b])	10	**20**	0
Release(lock[b])	Acquire(lock[b])	10	20	0
	Read(b) = 20	10	20	20
	Release(lock[b])	10	20	20
	Acquire(lock[a])	10	20	20
	Read(a) = 10	10	20	30
	Release(lock[a])	10	20	30
Acquire(lock[a])		10	20	30
Read(a) = 10		10	20	30

Time

Accessing multiple records

`Transfer (alice, bob, 10)` `Audit()`

Thread 0 (Transfer)	Thread 1 (Audit)	Bank[Alice]	Bank[bob]	Sum
		10	10	0
Acquire(lock[b])	Acquire(lock[b])	10	10	0
Read(b) = 10	Acquire(lock[b])	10	10	0
Write(b) = 20	Acquire(lock[b])	10	**20**	0
Release(lock[b])	Acquire(lock[b])	10	20	0
	Read(b) = 20	10	20	20
	Release(lock[b])	10	20	20
	Acquire(lock[a])	10	20	20
	Read(a) = 10	10	20	30
	Release(lock[a])	10	20	30
Acquire(lock[a])		10	20	30
Read(a) = 10		10	20	30
Write(a) = 0		**0**	**20**	**30**

Time

Accessing multiple records

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Thread 0 (Transfer)	Thread 1 (Audit)	Bank[Alice]	Bank[bob]	Sum
		10	10	0
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Read(b) = 10	Acquire(lock[b])	10	10	0
Write(b) = 20	Acquire(lock[b])	10	**20**	0
Release(lock[b])	Acquire(lock[b])	10	20	0
	Read(b) = 20	10	20	20
	Release(lock[b])	10	20	20
	Acquire(lock[a])	10	20	20
	Read(a) = 10	10	20	20
	Release(lock[a])	10	20	30
Acquire(lock[a])		10	20	30
Read(a) = 10		10	20	30
Write(a) = 0		**0**	**20**	**30**
Release(lock[a])		**0**	**20**	**30**

Time

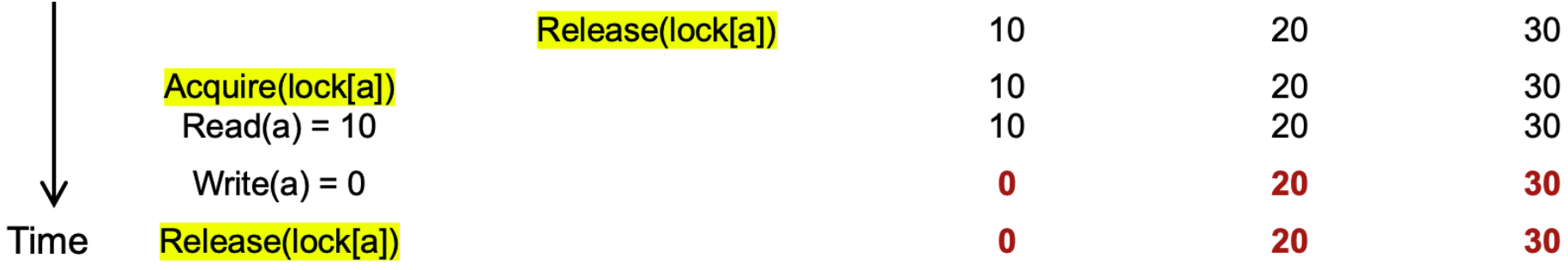
Problem: accessing multiple records

Question #1:

- Is the final state of the program correct (i.e., bank accounts) ?

Question #2:

- Is the sum of the audit correct?



Problem: accessing multiple records

Core problem

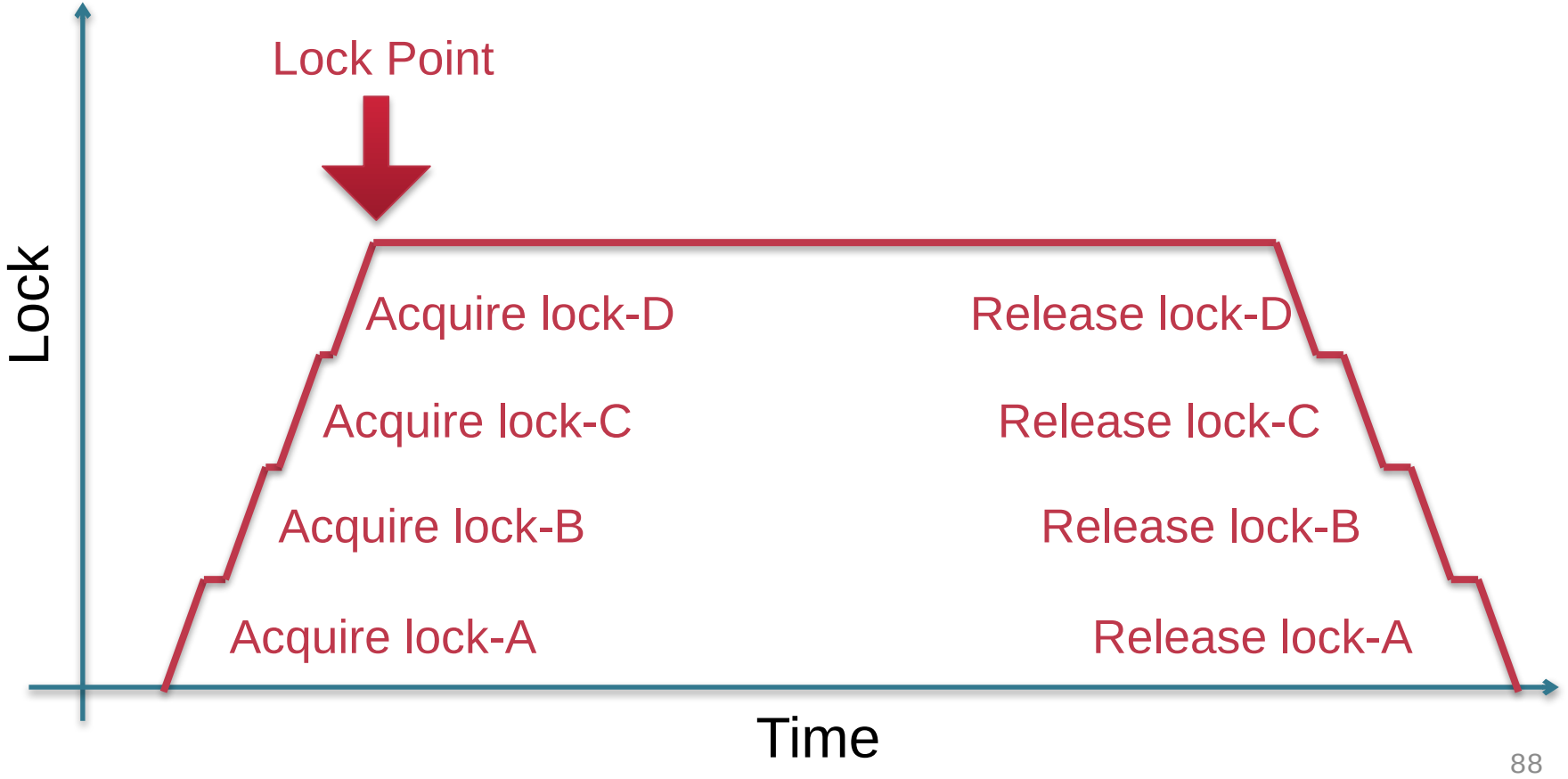
- Simple fine-grained locking does not prevent the exposure of intermediate result

Insight

- we need to delay the lock release time for each shared data
    - Until all the transaction's updates finish

Write(b) = 20	Acquire(lock[b])	10	20	0
Release(lock[b])	Acquire(lock[b])	10	20	10
	Read(b) = 20	10	20	10
	Release(lock[b])	10	20	10
	Acquire(lock[a]) Read(a) = 10	10 10	20 20	10 30

Solution: acquire all locks first, and release them at last



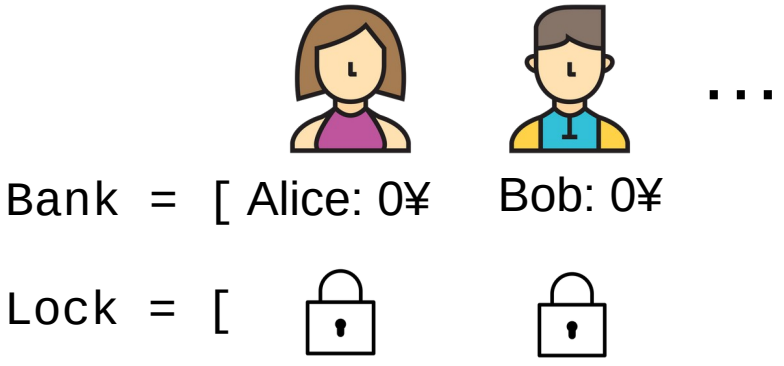
Two-phase locking (2PL)

Fine-grained locking:

- Each shared data has one lock
- E.g., a lock for Alice & a lock for Bob

2PL locking rule:

- The action must acquire the shared data's lock before access it, ~~and releases it after the data access finishes~~ and release it until the action finishes



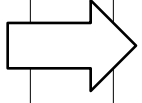
Two-phase locking (2PL)

2PL Lock acquire rule:

- The action must acquire the shared data's lock before access it, and release it until all the action finishes

Fine-grained locking

```
Transfer(bank, locks, a, b,
amt):
    Acquire(lock[b]
    bank[b] += amt
    Release(lock[b])
    Acquire(lock[a])
    bank[a] -= amt
    Release(lock[a])
```



Fine-grained locking + **2PL**

```
Transfer(bank, locks, a, b,
amt):
    Acquire(lock[b]
    bank[b] += amt

    Acquire(lock[a])
    bank[a] -= amt
    Release(lock[a])
    Release(lock[b])
```

Two-phase locking (2PL)

`Transfer (alice, bob, 10)` `Audit()`

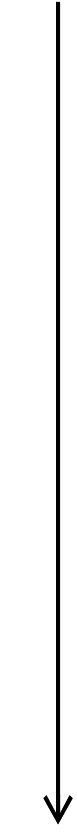
Thread 0 (Transfer)	Thread 1 (Audit)	Bank[Alice]	Bank[bob]	Sum
		10	10	0
Acquire(lock[b])	Acquire(lock[b])	10	10	0
Read(b) = 10	Acquire(lock[b])	10	10	0
Write(b) = 20	Acquire(lock[b])	10	**20**	0
~~Release(lock[b])~~	Acquire(lock[b])	10	20	0

Time

Two-phase locking (2PL)

`Transfer (alice, bob, 10)` `Audit()`

Thread 0 (Transfer)	Thread 1 (Audit)	Bank[Alice]	Bank[bob]	Sum
		10	10	0
Acquire(lock[b])	Acquire(lock[b])	10	10	0
Read(b) = 10	Acquire(lock[b])	10	10	0
Write(b) = 20	Acquire(lock[b])	10	**20**	0
Acquire(lock[a])	Acquire(lock[b])	10	20	0



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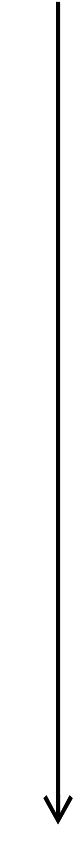
Acquire(lock[a])	Acquire(lock[b])	10	20	0
Read(a) = 10	Acquire(lock[b])	10	10	0



Two-phase locking (2PL)

```
Transfer
(alice, bob, 10)   Audit()
```

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		10	10	0
Acquire(lock[b])	Acquire(lock[b])	10	10	0
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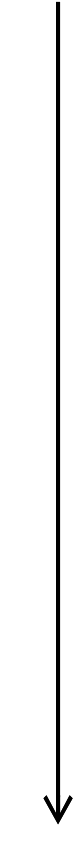
Acquire(lock[a])	Acquire(lock[b])	10	20	0
Read(a) = 10	Acquire(lock[b])	10	10	0
Write(a) = 0	Acquire(lock[b])	**0**	20	0



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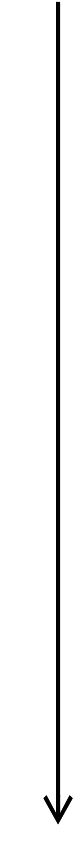
Acquire(lock[a])	Acquire(lock[b])	10	20	0
Read(a) = 10	Acquire(lock[b])	10	10	0
Write(a) = 0	Acquire(lock[b])	**0**	20	0
Release(lock[b])	Acquire(lock[b])	0	20	0



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Acquire(lock[a])	Acquire(lock[b])	10	20	0
Read(a) = 10	Acquire(lock[b])	10	10	0
Write(a) = 0	Acquire(lock[b])	**0**	20	0
Release(lock[b]) Release(lock[a])	Acquire(lock[b])	0	20	0
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Time

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Read(a) = 10	Acquire(lock[b])	10	10	0
Write(a) = 0	Acquire(lock[b])	**0**	20	0
Release(lock[b])	Acquire(lock[b])	0	20	0
Release(lock[a])				
	Read(b) = 20	0	20	20
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Time

Two-phase locking (2PL)

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Acquire(lock[a])	Acquire(lock[b])	10	20	0
Read(a) = 10	Acquire(lock[b])	10	10	0
Write(a) = 0	Acquire(lock[b])	**0**	20	0
Release(lock[b]) Release(lock[a])	Acquire(lock[b])	0	20	0
	Read(b) = 20	0	20	20
	Acquire(lock[a])	0	20	20
	Read(a) = 0	0	20	**20**

Time

Two-phase locking (2PL)

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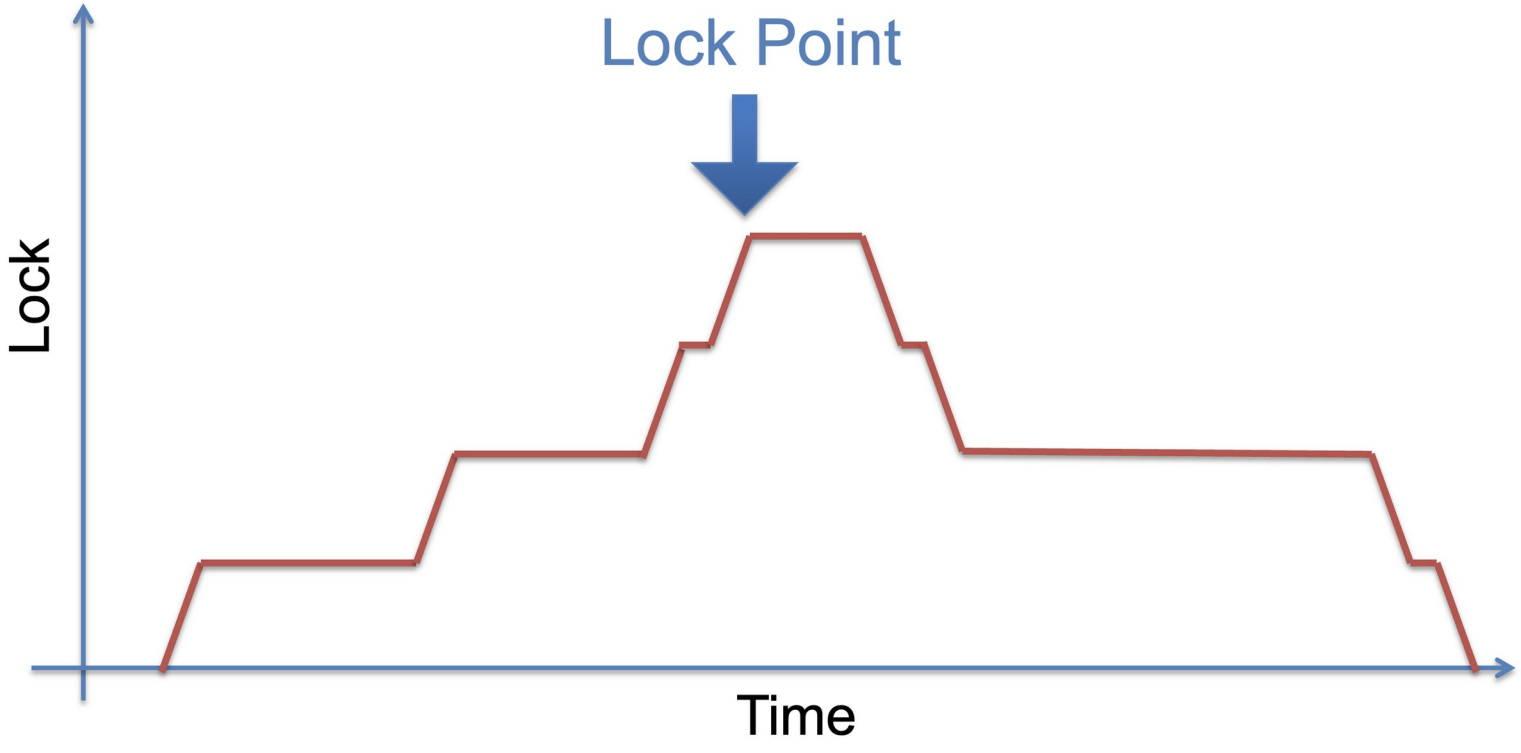
Acquire(lock[a])	Acquire(lock[b])	10	20	0
Read(a) = 10	Acquire(lock[b])	10	10	0
Write(a) = 0	Acquire(lock[b])	**0**	20	0
Release(lock[b]) Release(lock[a])	Acquire(lock[b])	0	20	0
	Read(b) = 20	0	20	20
	Acquire(lock[a])	0	20	20
	Read(a) = 0	0	20	**20**
	Release(lock[a])	0	20	**20**

Time

Audit appears to run after the transfer

Two-phase locking (2PL)



A note on fine-grained locking

The number of locks used is made explicit in our previous examples

- Global lock: only 1 lock
- 2PL (ideal): one per record

One lock per record record may waste many memory

- Especially when there are many records (e.g., records in files)

Configurable number of locks

- We can set a constant number of locks for the system
- Only need to ensure the access to the same record will acquire the same lock

Question: what are the trade-offs?

Use locking to achieve before-or-after: **2PL**

2PL can guarantee before or after atomicity with serializability

- Run actions T1, T2, .., TN concurrently, and have it "appears" as if they ran sequentially (we will prove it later)

Before or after atomicity also is usually termed as serializability

Before or after atomicity

Concurrent actions have the **before-or-after property** if their effect from the point of view of their invokers is as **if the actions occurred either completely before or completely after one another**

Serializability

2PL can guarantee before or after atomicity with serializability

- Run actions T1, T2, .., TN concurrently, and have it "appears" as if they ran sequentially (we will prove it later)

What does this mean?

Serializability

2PL can guarantee before or after atomicity with serializability

- Run actions T1, T2, .., TN concurrently, and have it "appears" as if they ran sequentially (we will prove it later)

What does this mean?

T1

```
begin
read(x)
tmp = read(y)
write(y, tmp+10)
commit
```

T2

```
begin
write(x, 20)
write(y, 30)
commit
```

Action start

Action end

T1

```
begin
read(x)
tmp = read(y)
write(y, tmp+10)
commit
```

T2

```
begin
write(x, 20)
write(y, 30)
commit
```

Init: x=0, y=0

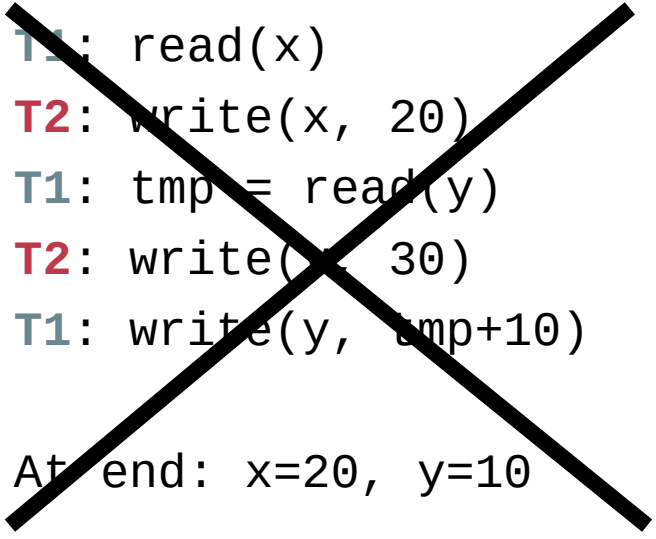
Possible sequential schedules

T1 -> T2: x=20, y=30

T2 -> T1: x=20, y=40

T2: write(x, 20)
T1: read(x)
T2: write(y, 30)
T1: tmp = read(y)
T1: write(y, tmp+10)

At end: x=20, y=40



T1	T2
begin	**begin**
read(x)	write(x, 20)
tmp = read(y)	write(y, 30)
write(y, tmp+10)	**commit**
commit	

Init: x=0, y=0

Possible sequential schedules

T1 -> T2: x=20, y=30

T2 -> T1: x=20, y=40

T2: write(x, 20)
T1: read(x)
T2: write(y, 30)
T1: tmp = read(y)
T1: write(y, tmp+10)

At end: x=20, y=40

T1: read(x) **x=0**
T2: write(x, 20)
T2: write(y, 30)
T1: tmp = read(y) **y=30**
T1: write(y, tmp+10)

At end: x=20, y=40

In the second schedule, the results are correct. But T1 reads **x=0 and y=30**; those reads are not possible in a sequential schedule. **Is that ok?**

Whether OK depends:

- There are many ways for multiple transactions to "appear" to have been run in sequence; there are different notions of serializability
- Chose a type of serializability depends on applications

```
T2: write(x, 20)
T1: read(x)
T2: write(y, 30)
T1: tmp = read(y)
T1: write(y, tmp+10)

At end: x=20, y=40
```

```
T1: read(x)          x=0
T2: write(x, 20)
T2: write(y, 30)
T1: tmp = read(y)    y=30
T1: write(y, tmp+10)

At end: x=20, y=40
```

In the second schedule, the results are correct. But T1 reads **x=0 and y=30**; those reads are not possible in a sequential schedule. **Is that ok?**

Serializability has many types

Final-state serializability

- A schedule is final-state serializable if its final written state is equivalent to that of some serial schedule

Conflict serializability ⇦ Most widely used

View serializability

Final-state serializability

```
T1: read(x)          x=0
T2: write(x, 20)
T2: write(y, 30)
T1: tmp = read(y)    y=30
T1: write(y, tmp+10)

At end: x=20, y=40
```

Conflict Serializability

Conflict Serializability

Two operations conflict if:

1. they operate on the same data object, and
2. at least one of them is write, and
3. they belong to different transactions

Conflict serializability

- A schedule is conflict serializable if **the order of its conflicts** (the order in which the conflicting operations occur) is **the same as the order of conflicts in some sequential schedule**

	T1		T2
	begin		**begin**
T1.1	read(x)	T2.1	write(x, 20)
T1.2	tmp = read(y)	T2.2	write(y, 30)
T1.3	write(y, tmp+10)		**commit**
	commit		

Init: x=0, y=0

Possible sequential schedules

T1 -> T2: x=20, y=30

T2 -> T1: x=20, y=40

Conflicts

T1.1 read(x) and T2.1 write(x,20) on x

T1.2 tmp = read(y) and T2.2 write(y,30) on y

T1.3 write(y, tmp+10) and T2.2 write(y,30) on y

Conflict Graph

Conflict Graph

- Nodes are transactions, edges are directed
- Edge between T_i and T_j if and only if:
    1. T_i and T_j have a conflict between them, and
    2. the first step in the conflict occurs in T_i

A schedule is conflict serializable if and only if:

- It has an **acyclic** conflict graph

T1

```
begin
read(x)
tmp = read(y)
write(y, tmp+10)
commit
```

T2

```
begin
write(x, 20)
write(y, 30)
commit
```

Possible sequential schedules

```
T1 -> T2: x=20, y=30
T2 -> T1: x=20, y=40
```

Conflicts

```
T1.1 read(x)        ->  T2.1 write(x,20)
T1.2 tmp = read(y)  ->  T2.2 write(y,30)
T1.3 write(y, tmp+10) ->  T2.2 write(y,30)
```

(T1 -> T2)

T1

```
begin
read(x)
tmp = read(y)
write(y, tmp+10)
commit
```

T2

```
begin
write(x, 20)
write(y, 30)
commit
```

Possible sequential schedules

```
T1 -> T2: x=20, y=30
T2 -> T1: x=20, y=40
```

Conflicts

T2.1 write(x,20) -> T1.1 read(x)

T2.2 write(y,30) -> T1.2 tmp = read(y)

T2.2 write(y,30) -> T1.3 write(y, tmp+10)

(T2 -> T1)

Conflicts

T2.1, T1.1
T2.2, T1.2
T2.2, T1.3

Conflict order for sequential schedules

T1.1 -> T2.1
T1.2 -> T2.2
T1.3 -> T2.2
(T1 -> T2)

or

T2.1 -> T1.1
T2.2 -> T1.2
T2.2 -> T1.3
(T2 -> T1)

T2: write(x, 20)
T1: read(x)
T2: write(y, 30)
T1: tmp = read(y)
T1: write(y, tmp+10)

T2.1 -> T1.1
T2.2 -> T1.2
T2.2 -> T1.3

~~**T1**: read(x)~~
~~**T2**: write(x, 20)~~
~~**T2**: write(y, 30)~~
~~**T1**: tmp = read(y)~~
~~**T1**: write(y, tmp+10)~~

T1.1 -> T2.1
T2.2 -> T1.2
T2.2 -> T1.3

Conflicts

T2.1, T1.1
T2.2, T1.2
T2.2, T1.3

Conflict order for sequential schedules

T1.1 -> T2.1
T1.2 -> T2.2
T1.3 -> T2.2
(T1 -> T2)

or

T2.1 -> T1.1
T2.2 -> T1.2
T2.2 -> T1.3
(T2 -> T1)

T2: write(x, 20)
T1: read(x)
T2: write(y, 30)
T1: tmp = read(y)
T1: write(y, tmp+10)

T2 -> T1

Both at end: x=20, y=40

T1: read(x)
T2: write(x, 20)
T2: write(y, 30)
T1: tmp = read(y)
T1: write(y, tmp+10)

T2 -->
T1 <--

It's final-state serializable, not conflict serializable

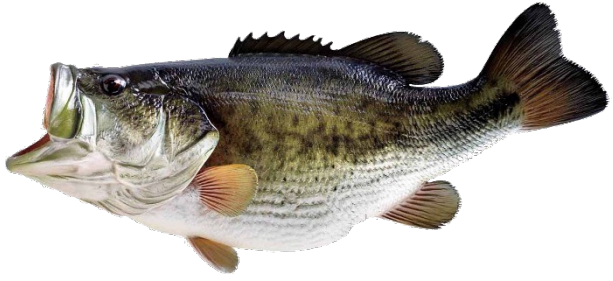
Conflict Equivalence

Schedule A

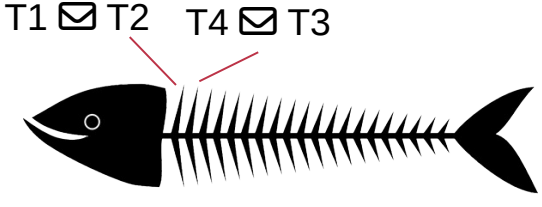
conflict-equal

if

equal



Schedule B



Conflicts order A

Conflicts order B

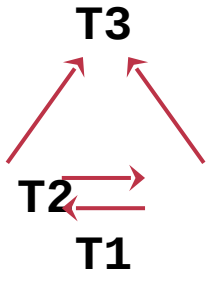
If conflicts-order-A equals to conflicts-order-B,
then schedule-A conflict-equals to schedule-B

View Serializability

```
T1          T2          T3
read(x)
            write(x)
write(x)

write(x)
```

Conflict graph



Cyclic -> Not conflict serializable

But compare it to running T1 then T2 then T3 (serially)

- Final-state is fine
- Intermediate reads are fine

Question: why shouldn't we allow this schedule?

View Serializability

Informal definition

- *A schedule is view serializable if the final written state as well as intermediate reads are the same as in some serial schedule*

Formally, for those interested

- Two schedules **S** and **S'** are **view equivalent** if:
  - If T_i in S reads an initial value for X, so does T_i in S'
  - If T_i in S reads the value written by T_j in S for some X, so does T_i in S'
  - If T_i in S does the final write to X, so does T_i in S'

A schedule is **view serializable** if it is **view equivalent** to some serial schedule

Question

Why conflict serializability when it seems too strict?

Why not focus on view serializability?

Final-state Serializability	⊃	**View Serializability**	⊃	**Conflict Serializability**
Care the final state only		Care the final state as well as intermediate read		Care the final state as well as all the **data dependency**

Conflict Serializability VS. View Serializability

Conflict serializability is easy to test

- i.e., check whether a graph is acyclic
- View serializability is hard to test (likely NP-hard)

Conflict serializable schedules are easy to generate

- Using concurrency control protocols. E.g., 2PL (**two-phase-locking**)

Conflict serializable schedules are also view serializable

- No easy way to generate view schedules that allows for ones like the previous example

Use locking to achieve before-or-after: **2PL**

2PL can guarantee before or after atomicity

- Run actions T1, T2, .., TN concurrently, and have it "appears" as if they ran sequentially

2PL locking rule:

- The action must acquire the shared data's lock before access it and release it until the action finishes

Question

- Which serializability does 2PL guarantee?
- Conflict serializability!

Proof of 2PL

Suppose 2PL does **not** generate conflict serializable schedule

Suppose the conflict graph produced by an execution of 2PL has a cycle, which without loss of generality, is:

T1 --> T2 --> ... --> Tk --> T1

Let the shared variable (the one that causes the conflict) between **T_i** and **T_{i+1}** be represented by **x_i**.

```
T1 and T2 conflict on x1
T2 and T3 conflict on x2
...
Tk and T1 conflict on x_k
```

```
T1 acquires x1.lock
T2 acquires x1.lock and x2.lock
T3 acquires x2.lock and x3.lock
...
Tk acquires x_{k-1}.lock and x_k.lock
T1 acquires x_k.lock
```

T1 violates 2PL!

```
T1 acquires x1.lock
T1 releases x1.lock
T2 acquires x1.lock and x2.lock
...
Tk acquires x_{k-1}.lock and x_k.lock
T1 acquires x_k.lock
```

```
T1 acquires x1.lock
T1 releases x1.lock
...
...
...
T1 acquires x_k.lock
```

Serializability simplifies enforcing concurrent correctness / data consistency

Correctness (app-semantic consistency)

Correctness is hard for computer system to enforce

- It is at the application level, with application specific semantic
- E.g., developer can write a buggy program, even no concurrency (single-threaded)

```
Transfer(bank, a, b,
amt):
    bank[b] += amt
    bank[a] -= amt
```

Buggy

```
Transfer(bank, a, b,
amt):
    bank[b] += amt * 2
    bank[a] -= amt
```

To ensure concurrent correctness, we need assumptions

- i.e., The single-threaded implementation of actions must be correct

Correctness and serializability

Assumption: programmers are pro at writing single-thread programs

- Specially, in a single-thread context, can move data from a consistent state （） to another consistent state （）

Then, if the execution of actions guarantee serializability, then the final state of concurrent execution is consistent

- i.e., the concurrent execution can reduce to If C0 is consistent, then Cn must be consistent

The deadlock issues of 2PL

Deadlock

Two-phase lock is pessimistic:

- Before proceed, each TX must wait for conflicting TX to release the lock
- What can happen if two TX are waiting for each other?

Deadlock: what if Thread 1 first acquires lock[a]?

Thread 0 (Transfer)	Thread 1 (Audit)	Bank[Alice]	Bank[bob]	Sum
		10	10	0
Acquire(lock[b])	Acquire(lock[b])	10	10	0
Read(b) = 10	Acquire(lock[b])	10	10	0
Write(b) = 20	Acquire(lock[b])	10	**20**	0
Acquire(lock[a])	Acquire(lock[b])	10	20	0
Read(a) = 10	Acquire(lock[b])	10	10	0
Write(a) = 0	Acquire(lock[b])	**0**	20	0
Release(lock[b])	Acquire(lock[b])	0	20	0
	Read(b) = 20	0	20	20
	Acquire(lock[a])	0	20	20
	Read(a) = 0	0	20	**20**
	Release(lock[a])	0	20	**20**

Deadlock: what if Thread 1 first acquires lock[a]?

Thread 0 (Transfer)	Thread 1 (Audit)	Bank[Alice]	Bank[bob]	Sum
		10	10	0
Acquire(lock[b])	**Acquire(lock[a])**	10	10	0

Deadlock: what if Thread 1 first acquires lock[a]?

Thread 0 (Transfer)	Thread 1 (Audit)	Bank[Alice]	Bank[bob]	Sum
		10	10	0
Acquire(lock[b])	**Acquire(lock[a])**	10	10	0
Read(b) = 10	Read(a) = 10	10	10	10

Deadlock: what if Thread 1 first acquires lock[a]?

Thread 0 (Transfer)	Thread 1 (Audit)	Bank[Alice]	Bank[bob]	Sum
		10	10	0
Acquire(lock[b])	**Acquire(lock[a])**	10	10	0
Read(b) = 10	Read(a) = 10	10	10	10
Acquire(lock[a])	**Acquire(lock[b])**			

Deadlock: what if Thread 1 first acquires lock[a]?

Thread 0 (Transfer)	Thread 1 (Audit)	Bank[Alice]	Bank[bob]	Sum
		10	10	0
Acquire(lock[b])	**Acquire(lock[a])**	10	10	0
Read(b) = 10	Read(a) = 10	10	10	10
Acquire(lock[a])	**Acquire(lock[b])**			
Acquire(lock[a])	**Acquire(lock[b])**			

Question: can thread 0 or thread 1 finishes the execution?

Resolving deadlock

1. Acquire locks in a pre-defined order

- Not support general TX: TX must know the read/write sets before execution

2. Detect deadlock by calculating the conflict graph

- If there is a cycle, then there must be a deadlock
- Abort one TX to break the cycle
- High cost for detection

3. Using heuristics (e.g., timestamp) to pre-abort the TXs

- May have false positive, or live locks