6.033 Spring 2019

Lecture #17

- **Isolation**
  - **Conflict serializability**
  - **Conflict graphs**
  - **Two-phase locking**

goal: build reliable systems from unreliable components

the abstraction that makes that easier is

transactions, which provide **atomicity** and **isolation**, while not hindering **performance**

atomicity ⟶ **shadow copies** (simple, poor performance) or **logs** (better performance, a bit more complex)

isolation ⟶ **?**

eventually, we also want transaction-based systems to be **distributed**: to run across multiple machines

goal: build reliable systems from unreliable components

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transactions, which provide **atomicity** and **isolation**, while not hindering **performance**

atomicity → **shadow copies** (simple, poor performance) or **logs** (better performance, a bit more complex)

isolation → **two-phase locking**

eventually, we also want transaction-based systems to be **distributed**: to run across multiple machines

goal: run transactions `T1`, `T2`, .., `TN` concurrently, and have it "appear" as if they ran sequentially

```
T1
begin
read(x)
tmp = read(y)
write(y, tmp+10)
commit
```

```
T2
begin
write(x, 20)
write(y, 30)
commit
```

naive approach: actually run them sequentially, via (perhaps) a single global lock

goal: run transactions `T1`, `T2`, .., `TN` concurrently, and have it "appear" as if they ran sequentially

what does this even mean?

```
T1
begin
read(x)
tmp = read(y)
write(y, tmp+10)
commit
```

```
T2
begin
write(x, 20)
write(y, 30)
commit
```

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

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

at end:

x=20, y=10

(assume x, y initialized to zero)

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

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

at end:
`x=20, y=10`

(assume x, y initialized to zero)

```
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
```

```
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, **T1** reads `x=0` *and* `y=30`; those two reads together aren't possible in a sequential schedule.
is that okay?

it depends.

there are many ways for multiple transactions to "appear" to have been run in sequence; we say there are different notions of **serializability**. what type of serializability you want depends on what your application needs.

conflicts

two operations conflict if they operate on the same object and at least one of them is a write.

```
T1
begin
T1.1 read(x)
T1.2 tmp = read(y)
T1.3 write(y, tmp+10)
commit
```

```
T2
begin
T2.1 write(x, 20)
T2.2 write(y, 30)
commit
```

---

conflicts

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

conflicts

two operations conflict if they operate on the same object and at least one of them is a write.

in any schedule, two conflicting operations A and B will have an order: either A is executed before B, or B is executed before A. we'll call this the **order** of the conflict (in that schedule).

```
T1
begin
T1.1 read(x)
T1.2 tmp = read(y)
T1.3 write(y, tmp+10)
commit
```

```
T2
begin
T2.1 write(x, 20)
T2.2 write(y, 30)
commit
```

---

conflicts

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

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

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

```
T1
begin
T1.1 read(x)
T1.2 tmp = read(y)
T1.3 write(y, tmp+10)
commit
```

```
T2
begin
T2.1 write(x, 20)
T2.2 write(y, 30)
commit
```

---

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)
```

if we execute T1 before T2, within any conflict, T1's operation will occur first

```
T1
begin
T1.1 read(x)
T1.2 tmp = read(y)
T1.3 write(y, tmp+10)
commit
```

```
T2
begin
T2.1 write(x, 20)
T2.2 write(y, 30)
commit
```

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)
```

if we execute **T2** before **T1**, within any conflict, **T2**'s operation will occur first

conflicts

two operations conflict if they operate on the same object and at least one of them is a write.

conflict serializability

a schedule is **conflict serializable** if the order of all of its conflicts is the same as the order of the conflicts in some sequential schedule.

conflicts

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

a schedule is **conflict serializable** if the order of all of its conflicts is the same as the order of the conflicts in some sequential schedule.

(here, that means we will see one transaction's — T1's or T2's — operation occurring first in each conflict)

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

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

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

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

conflicts

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

a schedule is **conflict serializable** if the order of all of its conflicts is the same as the order of the conflicts in some sequential schedule.

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```
T2.1: write(x, 20)
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T2.1 -> T1.1
T2.2 -> T1.2
T2.2 -> T1.3

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

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

conflict graph

edge from $\mathtt{T_i}$ to $\mathtt{T_j}$ iff $\mathtt{T_i}$ and $\mathtt{T_j}$ have a conflict between them and the first step in the conflict occurs in $\mathtt{T_i}$

```
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
```

conflict graph

edge from T_i to T_j iff T_i and T_j have a conflict between them and the first step in the conflict occurs in T_i

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

T2 → T1

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

T2 ⇄ T1

a schedule is conflict serializable iff it has an acyclic conflict graph

problem: how do we generate schedules that are conflict serializable? generate all possible schedules and check their conflict graphs?

solution: two-phase locking (2PL)

1. each shared variable has a lock
2. before **any** operation on a variable, the transaction must acquire the corresponding lock
3. after a transaction releases a lock, it may **not** acquire any other locks

we will usually release locks after commit or abort, which is technically *strict* two-phase locking

2PL produces a conflict-serializable schedule

(equivalently, 2PL produces a conflict graph without a cycle)

proof: suppose not. then a cycle exists in the conflict graph

$$\begin{tikzcd} T_1 \arrow[r] & T_2 \arrow[r] & T_3 \arrow[r] & \dots \arrow[r] & T_k \arrow[llll, bend left] \end{tikzcd}$$

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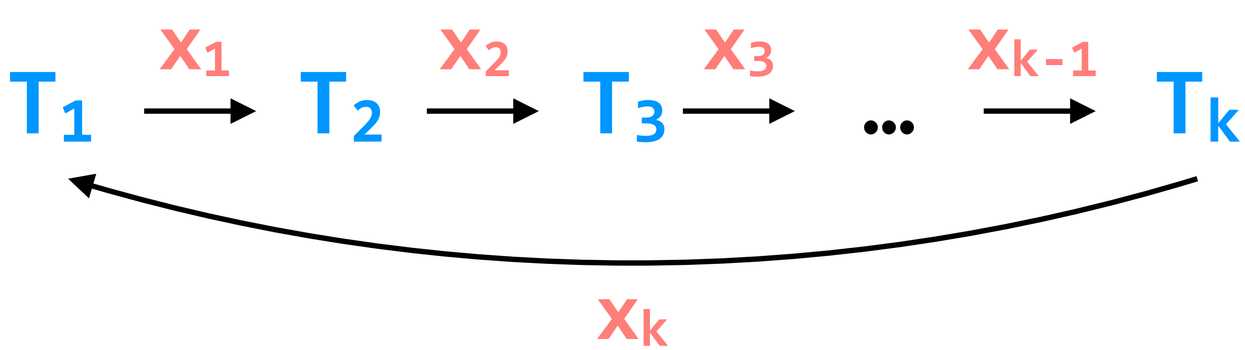
proof: suppose not. then a cycle exists in the conflict graph



to cause the conflict, each pair of conflicting **transactions** must have some **shared variable** that they conflict on

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proof: suppose not. then a cycle exists in the conflict graph

$$\begin{tikzcd} T_1 \arrow[r, "x_1"] & T_2 \arrow[r, "x_2"] & T_3 \arrow[r, "x_3"] & \cdots \arrow[r, "x_{k-1}"] & T_k \arrow[llll, bend left, "x_k"] \end{tikzcd}$$

to cause the conflict, each pair of conflicting **transactions** must have some **shared variable** that they conflict on

T_1 **acquires** x_1**.lock**
T_2 **acquires** x_1**.lock**

T_2 **acquires** x_2**.lock**
T_3 **acquires** x_2**.lock**

…

T_k **acquires** x_k**.lock**
T_1 **acquires** x_k**.lock**

in the schedule, each pair of **transactions** needs to acquire a lock on their **shared variable**

2PL produces a conflict-serializable schedule

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$$
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\end{tikzcd}
$$

to cause the conflict, each pair of conflicting **transactions** must have some **shared variable** that they conflict on

in the schedule, each pair of **transactions** needs to acquire a lock on their **shared variable**

T_1 **acquires** x_1**.lock**
T_1 **releases** x_1**.lock**
T_2 **acquires** x_1**.lock**

T_2 **acquires** x_2**.lock**
T_3 **acquires** x_2**.lock**

…

T_k **acquires** x_k**.lock**
T_1 **acquires** x_k**.lock**

in order for the schedule to progress, T_1 must have released its lock on x_1 before T_2 acquired it

2PL produces a conflict-serializable schedule

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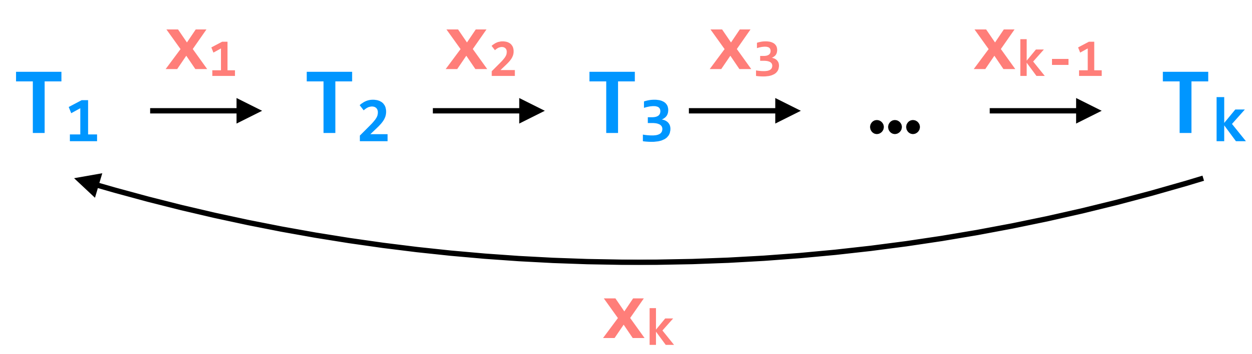

to cause the conflict, each pair of conflicting **transactions** must have some **shared variable** that they conflict on

T_1 **acquires** x_1**.lock**
T_1 **releases** x_1**.lock**
T_2 **acquires** x_1**.lock**

T_2 **acquires** x_2**.lock**
T_3 **acquires** x_2**.lock**

...

T_k **acquires** x_k**.lock**
T_1 **acquires** x_k**.lock**

in the schedule, each pair of **transactions** needs to acquire a lock on their **shared variable**

in order for the schedule to progress, T_1 must have released its lock on x_1 before T_2 acquired it

contradiction: this is not a valid 2PL schedule

T1	**T2**
`acquire(x.lock)`	`acquire(y.lock)`
`read(x)`	`read(y)`
`acquire(y.lock)`	`acquire(x.lock)`
`read(y)`	`read(x)`
`release(y.lock)`	`release(x.lock)`
`release(x.lock)`	`release(y.lock)`

problem: 2PL can result in deadlock

T1	**T2**
`acquire(x.lock)`	`acquire(y.lock)`
`read(x)`	`read(y)`
`acquire(y.lock)`	`acquire(x.lock)`
`read(y)`	`read(x)`
`release(y.lock)`	`release(x.lock)`
`release(x.lock)`	`release(y.lock)`

“solution”: global ordering on locks

```
T1                  T2
acquire(x.lock)     acquire(y.lock)
read(x)             read(y)
acquire(y.lock)     acquire(x.lock)
read(y)             read(x)
release(y.lock)     release(x.lock)
release(x.lock)     release(y.lock)
```

better solution: take advantage of atomicity and abort one of the transactions!

performance improvement: allow concurrent reads with reader- and writer-locks

T1
```
acquire(x.reader_lock)
read(x)
acquire(y.writer_lock)
write(y)
release(y.writer_lock)
release(x.reader_lock)
```

T2
```
acquire(x.reader_lock)
read(x)
acquire(y.writer_lock)
write(y)
release(y.writer_lock)
release(x.reader_lock)
```

multiple transactions can hold reader locks for the same variable at once. a transaction can only hold a writer lock for a variable if there are *no* other locks held for that variable

- Different types of **serializability** allow us to specify precisely what we want when we run transactions in parallel. **Conflict-serializability** is common in practice.

- **Two-phase locking** allows us to generate conflict serializable schedules. We can improve its performance by allowing concurrent reads via reader- and writer-locks.