6.1800 Spring 2024

Lecture #18: Isolation

what do we want from isolation, and how do we get it?

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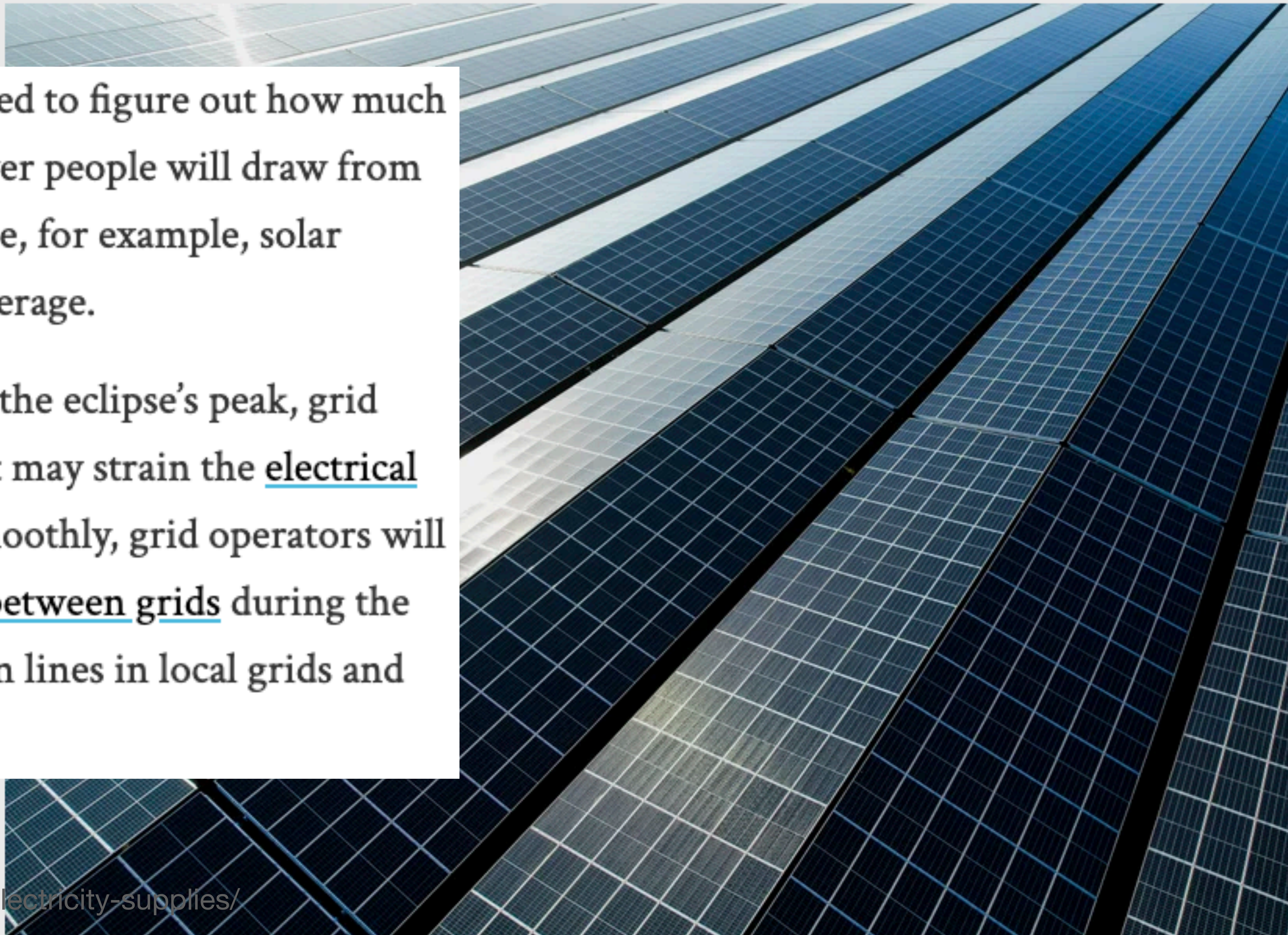
6.1800 in the news

MARCH 13, 2024 | 5 MIN READ

How the Solar Eclipse Will Impact Electricity Supplies

This April's total solar eclipse will present a unique challenge to power grid operators because of the decline in solar power generation

BY VAHE PEROOMIAN & THE CONVERSATION US

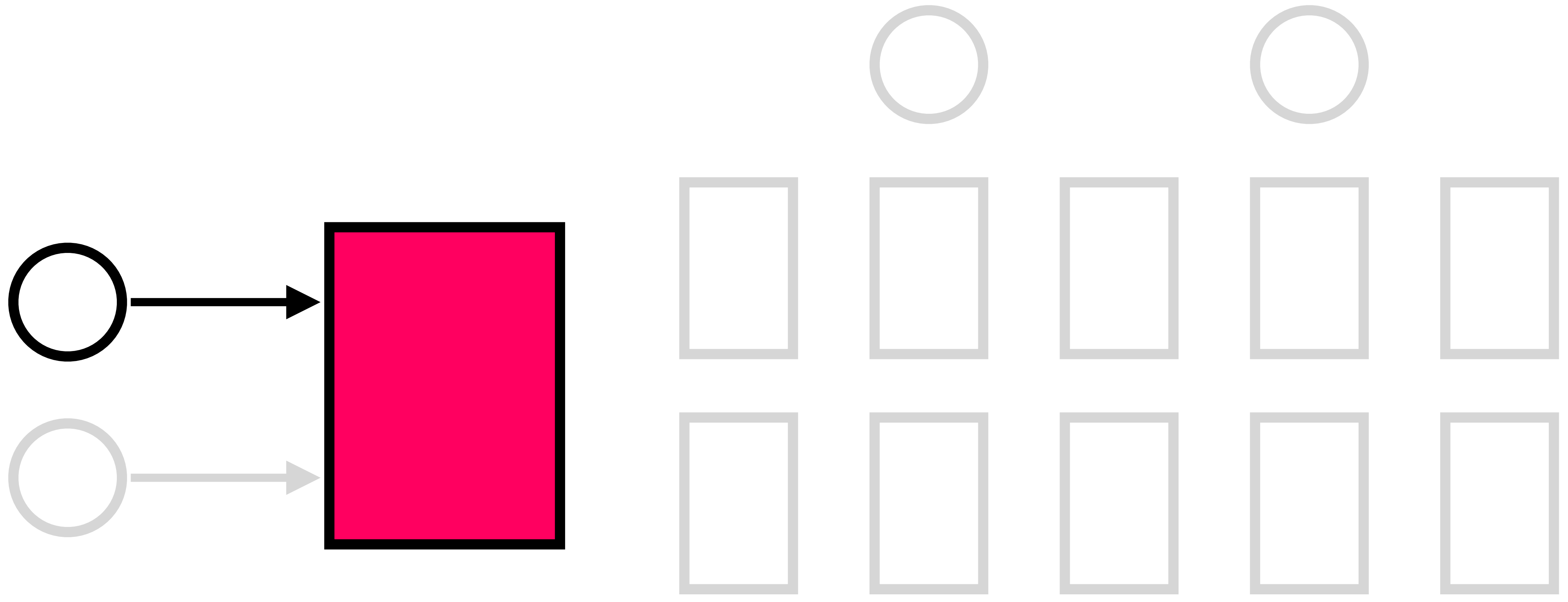


To plan for an eclipse, electrical system operators need to figure out how much the energy production will drop and how much power people will draw from the reserves. On the day of the 2017 total solar eclipse, for example, solar power generation in the U.S. dropped 25% below average.

Because solar power production falls quickly during the eclipse's peak, grid operators may need to tap into reserves at a rate that may strain the electrical transmission lines. To try to keep things running smoothly, grid operators will rely on local reserves and minimize power transfer between grids during the event. This should lessen the burden on transmission lines in local grids and prevent temporary blackouts.

https://www.scientificamerican.com/article/how-the-solar-eclipse-will-impact-electricity-supplies/

our goal is to build **reliable systems from unreliable components**. we want to build systems that serve many clients, store a lot of data, perform well, all while keeping availability high



transactions — which provide **atomicity** and **isolation** — make it easier for us to reason about failures

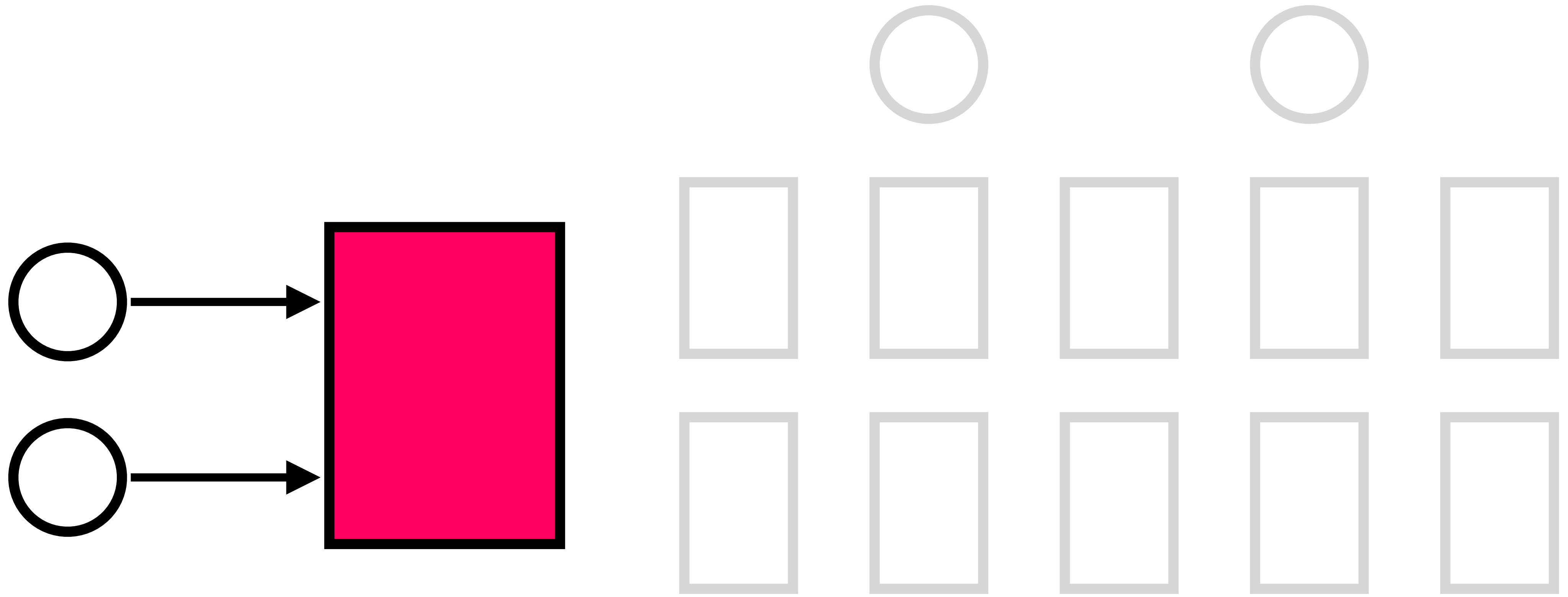
our job in lecture is to understand how a system *implements* these two abstractions. how do our systems guarantee atomicity? how do they guarantee isolation?

atomicity: provided by **logging**, which gives better performance than shadow copies* at the cost of some added complexity

* shadow copies *are* used in some systems

isolation: we don't really have this yet
(coarse-grained locks perform poorly; fine-grained locks are difficult to reason about)

our goal is to build **reliable systems from unreliable components**. we want to build systems that serve many clients, store a lot of data, perform well, all while keeping availability high



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atomicity: provided by **logging**, which gives better performance than shadow copies* at the cost of some added complexity

* shadow copies *are* used in some systems

isolation: provided by **two-phase locking**

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

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```
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
```

(assume x, y initialized to zero)

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

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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?**

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T1.1 read(x)
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```

```
T2
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T2.1 write(x, 20)
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(assume x, y initialized to zero)

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result: x=20; y=30
```

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

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T1.1 read(x)
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T2
begin
T2.1 write(x, 20)
T2.2 write(y, 30)
commit
```

(assume x, y initialized to zero)

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

result: x=20; y=30
```

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

result: x=20; y=40
```

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

```
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
```

(assume x, y initialized to zero)

```
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)            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)

result: x=20; y=30               result: x=20; y=40
```

let's look at a few different schedules of T1 and T2 (this is not an exhaustive list)

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

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	

(assume x, y initialized to zero)

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

result: x=20; y=30

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

result: x=20; y=40

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T2.1 write(x, 20)
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```

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

```
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
```

(assume x, y initialized to zero)

```
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)           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)

result: x=20; y=30              result: x=20; y=40
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```
T2.1 write(x, 20)               T1.1 read(x)
T1.1 read(x)                    T2.1 write(x, 20)
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T1.2 tmp = read(y)              T2.2 write(y, 30)
T1.3 write(y, tmp+10)           T1.3 write(y, tmp+10)
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goal: run transactions T1, T2 concurrently, and have it "appear" as if they ran sequentially

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

result: x=20; y=40         result: x=20; y=10
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result: x=20; y=10
```

```
T1.1 read(x) // x=0
T2.1 write(x, 20)
T2.2 write(y, 30)
T1.2 tmp = read(y) // y=30
T1.3 write(y, tmp+10)

result: x=20; y=40
```

but take a closer look at the third schedule; in the first step, T1.1 reads **x=0**, and in the fourth step, T1.2 reads **y=30**.

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

```
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
```

(assume x, y initialized to zero)

```
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)             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)

result: x=20; y=30                result: x=20; y=40
T1 reads x=0; y=0                 T1 reads x=20; y=30
```

let's look at a few different schedules of T1 and T2 (this is not an exhaustive list)

```
T2.1 write(x, 20)
T1.1 read(x)
T2.2 write(y, 30)
T1.2 tmp = read(y)
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result: x=20; y=40
```

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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)

result: x=20; y=10
```

```
T1.1 read(x) // x=0
T2.1 write(x, 20)
T2.2 write(y, 30)
T1.2 tmp = read(y) // y=30
T1.3 write(y, tmp+10)

result: x=20; y=40
```

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T1.3 write(y, tmp+10)           commit
commit
```

(assume x, y initialized to zero)

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

result: x=20; y=30              result: x=20; y=40
T1 reads x=0; y=0               T1 reads x=20; y=30
```

let's look at a few different schedules of T1 and T2 (this is not an exhaustive list)

```
T2.1 write(x, 20)          T1.1 read(x)               T1.1 read(x) // x=0
T1.1 read(x)               T2.1 write(x, 20)          T2.1 write(x, 20)
T2.2 write(y, 30)          T1.2 tmp = read(y)         T2.2 write(y, 30)
T1.2 tmp = read(y)         T2.2 write(y, 30)          T1.2 tmp = read(y) // y=30
T1.3 write(y, tmp+10)      T1.3 write(y, tmp+10)      T1.3 write(y, tmp+10)

result: x=20; y=40         result: x=20; y=10         result: x=20; y=40
```

but take a closer look at the third schedule; in the first step, T1.1 reads **x=0**, and in the fourth step, T1.2 reads **y=30**. those two reads together aren't possible in either 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
```

(assume x, y initialized to zero)

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
```

(assume x, y initialized to zero)

conflicts

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
```

(assume x, y initialized to zero)

conflicts

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

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
```

(assume x, y initialized to zero)

conflicts

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

`T1.2 tmp = read(y)` 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

```
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
```

(assume x, y initialized to zero)

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

```
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
```

(assume x, y initialized to zero)

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)`

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).

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

```
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
```

(assume x, y initialized to zero)

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)`

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).

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

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	

(assume x, y initialized to zero)

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)

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).

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

order of 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)
```

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
```

(assume x, y initialized to zero)

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)`

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).

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

order of conflicts

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

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
```

(assume x, y initialized to zero)

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)`

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).

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

order of conflicts

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

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

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
```

(assume x, y initialized to zero)

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)`

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).

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

order of conflicts

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

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

order of conflicts

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
```

(assume x, y initialized to zero)

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)
```

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).

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

order of conflicts

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

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

order of conflicts

```
T2.1 -> T1.1
```

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
```

(assume x, y initialized to zero)

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)`

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).

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

order of conflicts

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

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

order of conflicts

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

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
```

(assume x, y initialized to zero)

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)`

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).

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

order of conflicts

`T1.1 -> T2.1`

`T1.2 -> T2.2`

`T1.3 -> T2.2`

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

order of conflicts

`T2.1 -> T1.1`

`T2.2 -> T1.2`

`T2.2 -> T1.3`

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
```

(assume x, y initialized to zero)

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)`

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).

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

order of conflicts

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

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

order of conflicts

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

notice that, if we execute `T1` and `T2` serially, then in the ordering of the conflicts we see either *all* of `T1`'s operations occurring first, or *all* of `T2`'s operations occurring first

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

```
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
```

(assume x, y initialized to zero)

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)`

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).

```
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)
```

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
```

(assume x, y initialized to zero)

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)
```

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).

```
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)
```

order of conflicts

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

```
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
```

(assume x, y initialized to zero)

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)`

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).

```
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)
```

order of conflicts

`T2.1 -> T1.1`

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

```
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
```

(assume x, y initialized to zero)

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)
```

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).

```
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)
```

order of conflicts

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

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
```

(assume x, y initialized to zero)

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)`

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).

```
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)
```

order of conflicts

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

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
```

(assume x, y initialized to zero)

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)
```

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).

```
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)
```

order of conflicts

```
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)
```

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
```

(assume x, y initialized to zero)

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)`

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).

```
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)
```

order of conflicts

```
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)
```

order of conflicts

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

```
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
```

(assume x, y initialized to zero)

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)`

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).

```
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)
```

order of conflicts

```
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)
```

order of conflicts

```
T1.1 -> T2.1
```

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
```

(assume x, y initialized to zero)

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)`

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).

```
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)
```

order of conflicts

```
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)
```

order of conflicts

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

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

```
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
```

(assume x, y initialized to zero)

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)`

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).

```
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)
```

order of conflicts

```
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)
```

order of conflicts

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

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

```
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
```

(assume x, y initialized to zero)

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)`

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).

```
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)
```

order of conflicts

```
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)
```

order of conflicts

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

on the left schedule, the order of conflicts is the same as if we had run T2 entirely before T1; on the right schedule, the order of conflicts isn't the same as either serial schedule

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.

```
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
```

(assume x, y initialized to zero)

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)`

```
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)
```

order of conflicts

```
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)
```

order of conflicts

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

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.

```
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
```

(assume x, y initialized to zero)

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)`

```
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)
```

order of conflicts

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

this schedule is conflict serializable

```
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)
```

order of conflicts

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

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.

```
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
```

(assume x, y initialized to zero)

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)
```

```
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)
```

order of conflicts

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

this schedule is conflict serializable

```
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)
```

order of conflicts

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

this schedule is **not** conflict serializable

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.

```
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
```

(assume x, y initialized to zero)

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)`

we can express the order of conflicts more succinctly with a **conflict graph**: there is an edge from T_i to T_j if and only if T_i and T_j have a conflict between them and the first step in the conflict occurs in T_i

```
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)
```

order of conflicts

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

this schedule is conflict serializable

```
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)
```

order of conflicts

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

this schedule is **not** conflict serializable

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.

```
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
```

(assume x, y initialized to zero)

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)
```

we can express the order of conflicts more succinctly with a **conflict graph**: there is an edge from T_i to T_j if and only if T_i and T_j have a conflict between them and the first step in the conflict occurs in T_i

```
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)
```

conflict graph

T2 → T1

this schedule is conflict serializable

```
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)
```

conflict graph

T2 ⇄ T1

this schedule is **not** conflict serializable

interlude: practice with **conflict graphs**

```
T1
begin
T1.1 read(x)
T1.2 write(y, 10)
commit
```

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

```
T3
begin
T3.1 read(y)
T3.2 write(z, 40)
commit
```

```
T4
begin
T4.1 read(y)
commit
```

interlude: practice with **conflict graphs**

```
T1
begin
T1.1 read(x)
T1.2 write(y, 10)
commit
```

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

```
T3
begin
T3.1 read(y)
T3.2 write(z, 40)
commit
```

```
T4
begin
T4.1 read(y)
commit
```

```
T1.1 read(x)
T2.1 write(x, 20)
T3.1 read(y)
T4.1 read(y)
T1.2 write(y, 10)
T2.2 write(y, 30)
T3.2 write(z, 40)
```

interlude: practice with **conflict graphs**

```
T1
begin
T1.1 read(x)
T1.2 write(y, 10)
commit
```

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

```
T3
begin
T3.1 read(y)
T3.2 write(z, 40)
commit
```

```
T4
begin
T4.1 read(y)
commit
```

```
T1.1 read(x)
T2.1 write(x, 20)
T3.1 read(y)
T4.1 read(y)
T1.2 write(y, 10)
T2.2 write(y, 30)
T3.2 write(z, 40)
```

what is the conflict graph for this schedule?

interlude: practice with **conflict graphs**

```
T1
begin
T1.1 read(x)
T1.2 write(y, 10)
commit
```

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

```
T3
begin
T3.1 read(y)
T3.2 write(z, 40)
commit
```

```
T4
begin
T4.1 read(y)
commit
```

```
T1.1 read(x)
T2.1 write(x, 20)
T3.1 read(y)
T4.1 read(y)
T1.2 write(y, 10)
T2.2 write(y, 30)
T3.2 write(z, 40)
```

what is the conflict graph for this schedule?

T1 T2 T3 T4

interlude: practice with **conflict graphs**

```
T1
begin
T1.1 read(x)
T1.2 write(y, 10)
commit
```

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

```
T3
begin
T3.1 read(y)
T3.2 write(z, 40)
commit
```

```
T4
begin
T4.1 read(y)
commit
```

```
T1.1 read(x)
T2.1 write(x, 20)
T3.1 read(y)
T4.1 read(y)
T1.2 write(y, 10)
T2.2 write(y, 30)
T3.2 write(z, 40)
```

what is the conflict graph for this schedule?

interlude: practice with **conflict graphs**

```
T1
begin
T1.1 read(x)
T1.2 write(y, 10)
commit
```

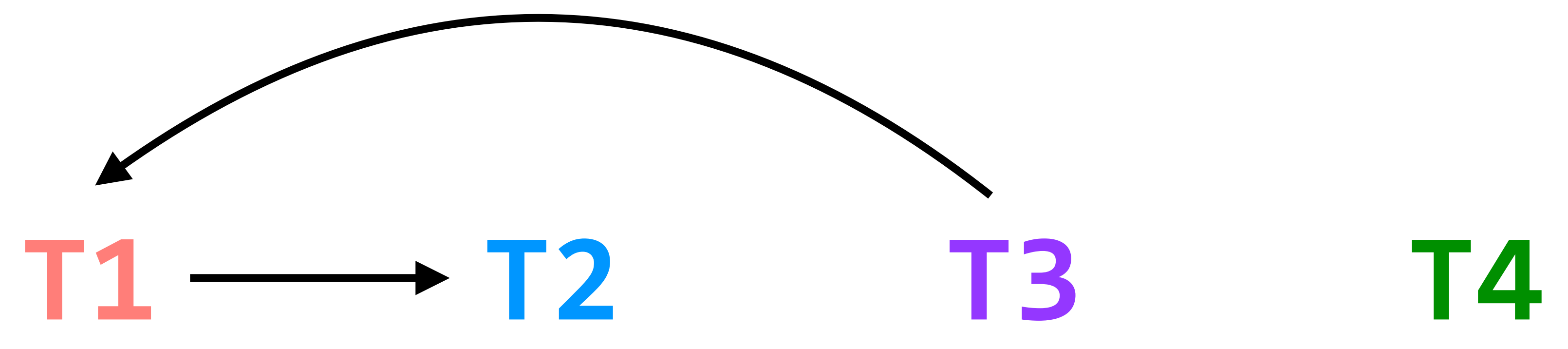
```
T2
begin
T2.1 write(x, 20)
T2.2 write(y, 30)
commit
```

```
T3
begin
T3.1 read(y)
T3.2 write(z, 40)
commit
```

```
T4
begin
T4.1 read(y)
commit
```

```
T1.1 read(x)
T2.1 write(x, 20)
T3.1 read(y)
T4.1 read(y)
T1.2 write(y, 10)
T2.2 write(y, 30)
T3.2 write(z, 40)
```

what is the conflict graph for this schedule?



interlude: practice with **conflict graphs**

```
T1
begin
T1.1 read(x)
T1.2 write(y, 10)
commit
```

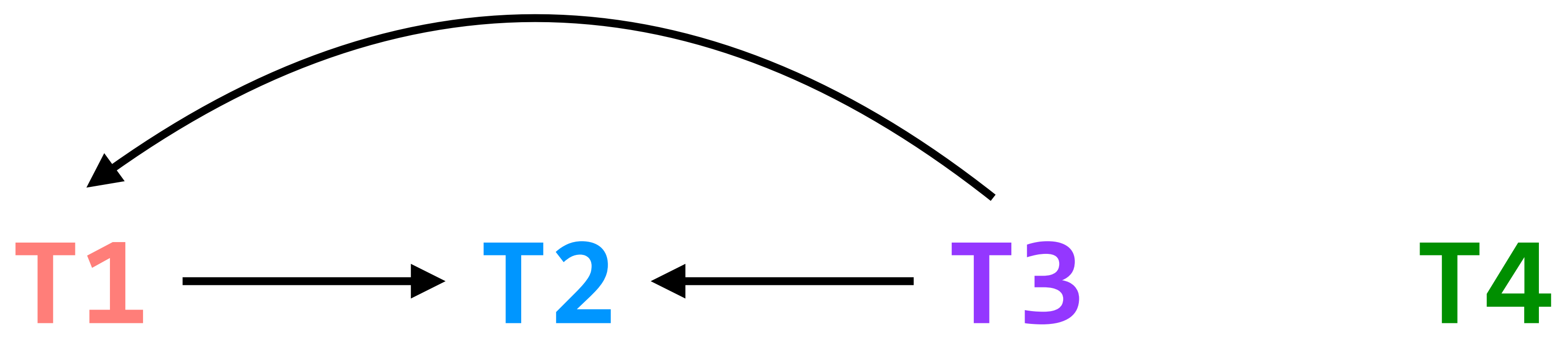
```
T2
begin
T2.1 write(x, 20)
T2.2 write(y, 30)
commit
```

```
T3
begin
T3.1 read(y)
T3.2 write(z, 40)
commit
```

```
T4
begin
T4.1 read(y)
commit
```

```
T1.1 read(x)
T2.1 write(x, 20)
T3.1 read(y)
T4.1 read(y)
T1.2 write(y, 10)
T2.2 write(y, 30)
T3.2 write(z, 40)
```

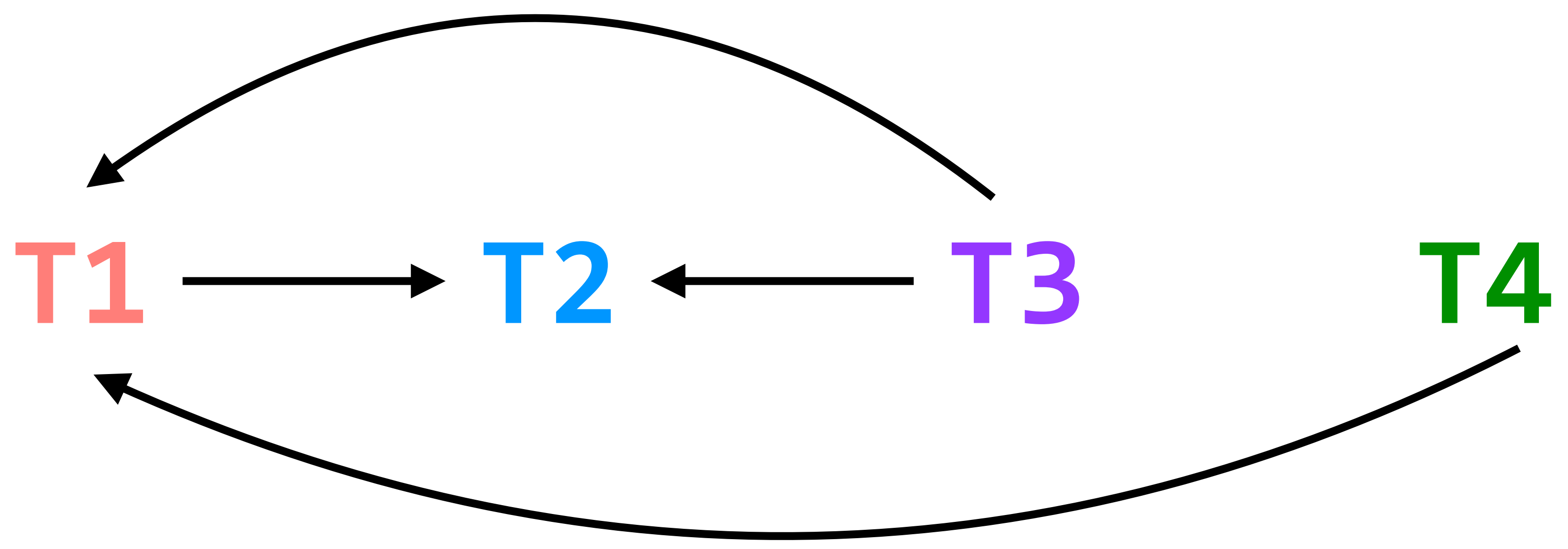
what is the conflict graph for this schedule?



interlude: practice with **conflict graphs**

T1	T2	T3	T4
begin	begin	begin	begin
T1.1 read(x)	T2.1 write(x, 20)	T3.1 read(y)	T4.1 read(y)
T1.2 write(y, 10)	T2.2 write(y, 30)	T3.2 write(z, 40)	commit
commit	commit	commit	

```
T1.1 read(x)
T2.1 write(x, 20)
T3.1 read(y)
T4.1 read(y)
T1.2 write(y, 10)
T2.2 write(y, 30)
T3.2 write(z, 40)
```



what is the conflict graph for this schedule?

interlude: practice with **conflict graphs**

```
T1
begin
T1.1 read(x)
T1.2 write(y, 10)
commit
```

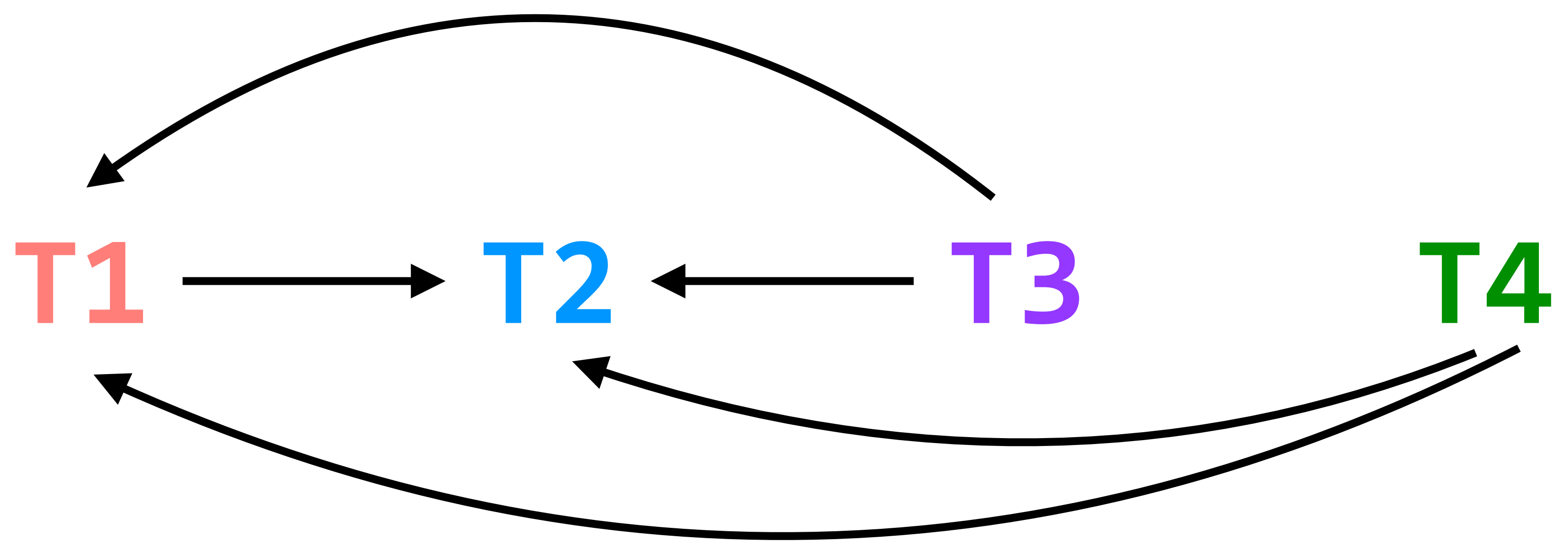
```
T2
begin
T2.1 write(x, 20)
T2.2 write(y, 30)
commit
```

```
T3
begin
T3.1 read(y)
T3.2 write(z, 40)
commit
```

```
T4
begin
T4.1 read(y)
commit
```

```
T1.1 read(x)
T2.1 write(x, 20)
T3.1 read(y)
T4.1 read(y)
T1.2 write(y, 10)
T2.2 write(y, 30)
T3.2 write(z, 40)
```

what is the conflict graph for this schedule?



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.

```
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
```

(assume x, y initialized to zero)

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)`

we can express the order of conflicts more succinctly with a **conflict graph**: there is an edge from T_i to T_j if and only if T_i and T_j have a conflict between them and the first step in the conflict occurs in T_i

```
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)
```

conflict graph

T2 → T1

this schedule is conflict serializable

```
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)
```

conflict graph

T2 ⇄ T1

this schedule is **not** conflict serializable

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.

```
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
```

(assume x, y initialized to zero)

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)`

we can express the order of conflicts more succinctly with a **conflict graph**: there is an edge from T_i to T_j if and only if T_i and T_j have a conflict between them and the first step in the conflict occurs in T_i

```
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)
```

conflict graph

T2 → T1

this schedule is conflict serializable

```
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)
```

conflict graph

T2 ⇄ T1

this schedule is **not** conflict serializable

a schedule is conflict serializable if and only if it has an acyclic conflict graph

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.

```
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
```

(assume x, y initialized to zero)

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)`

our goal (in lecture) is to run transactions concurrently, but to produce a schedule that is conflict serializable

how does a system do that? one way might be to generate all possible schedules and check their conflict graphs, and run one of the schedules with an acyclic conflict graph, but this will take some time

two-phase locking (2PL)

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1. each shared variable has a lock

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2. before **any** operation on a variable, the transaction must acquire the corresponding lock

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

two-phase locking (2PL)

2PL still gives us options for where we place the locks

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

two-phase locking (2PL)

2PL still gives us options for where we place the locks

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

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

two-phase locking (2PL)

2PL still gives us options for where we place the locks

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

```
T1
begin
acquire(x.lock)
acquire(y.lock)
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two-phase locking (2PL)

2PL still gives us options for where we place the locks

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we **can't** do this; it breaks the third rule of 2PL

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```
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if we release locks after commit, that is technically *strict* two-phase locking

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T2
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release(x.lock)
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```

notice that with this approach to 2PL, we will effectively force these two transactions to run serially. we'll address that in a few slides!

there are some lingering issues related to possible deadlocks and performance; we'll deal with those, but let's first try to understand why 2PL produces a conflict-serializable schedule

two-phase locking (2PL)

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2PL produces a conflict-serializable schedule

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

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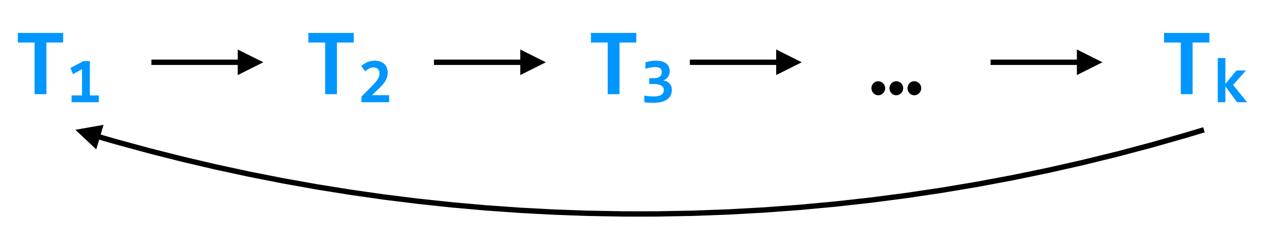

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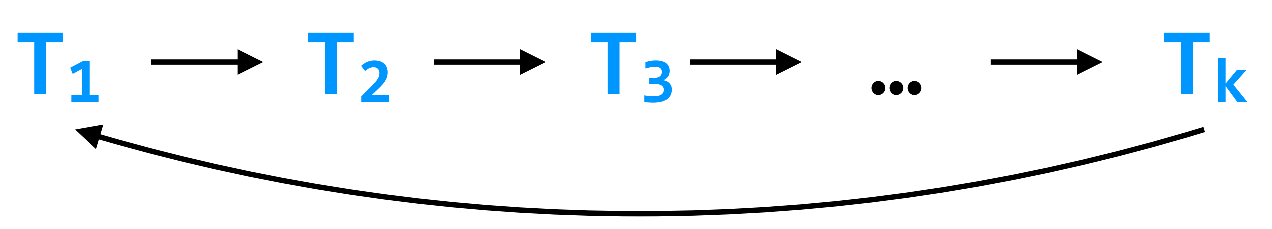

to cause the conflict, each pair of conflicting **transactions** must have some **shared variable** that they conflict on

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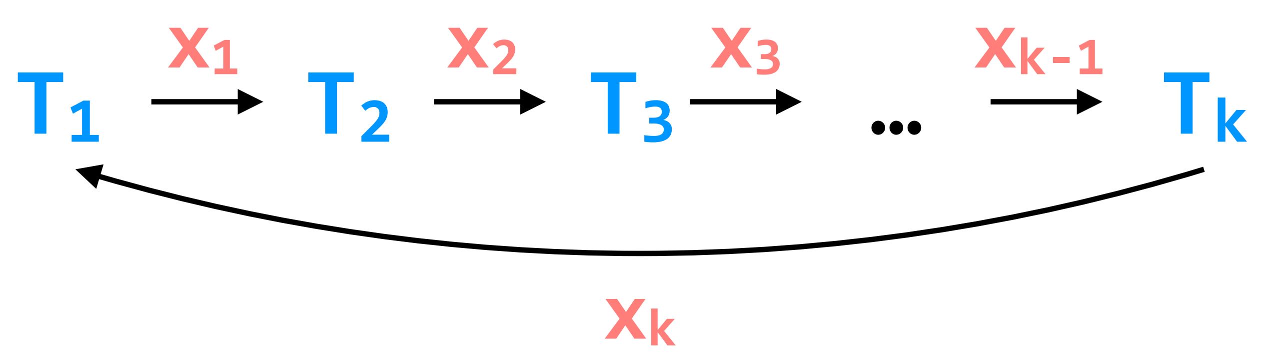

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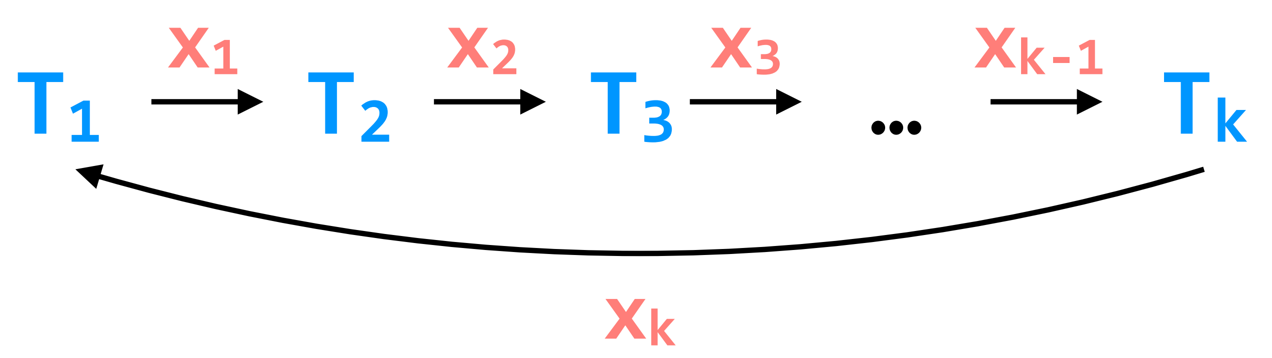

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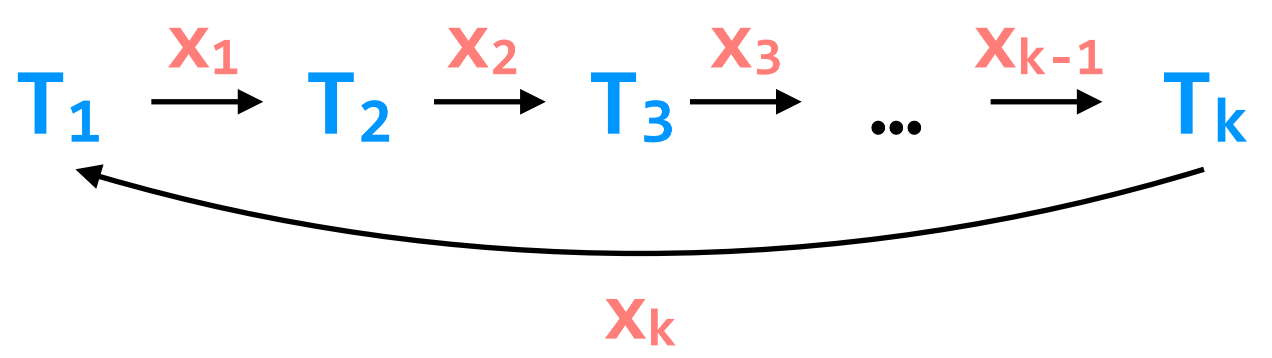

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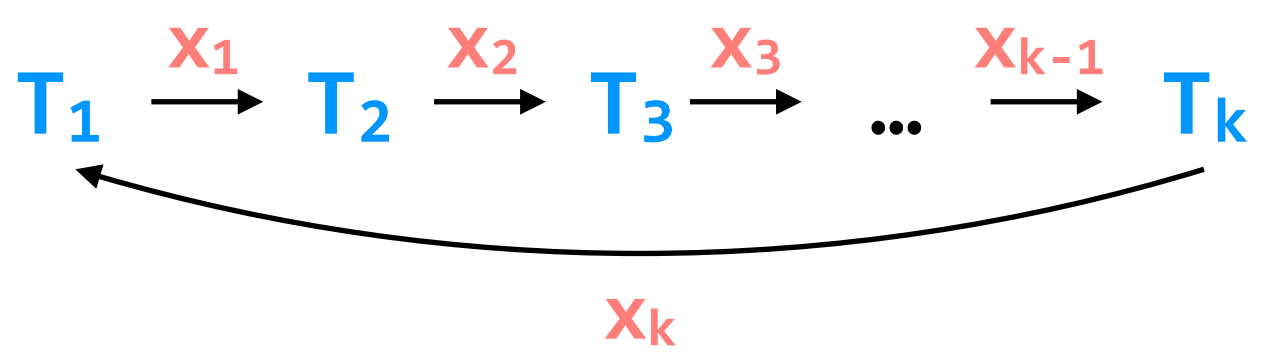

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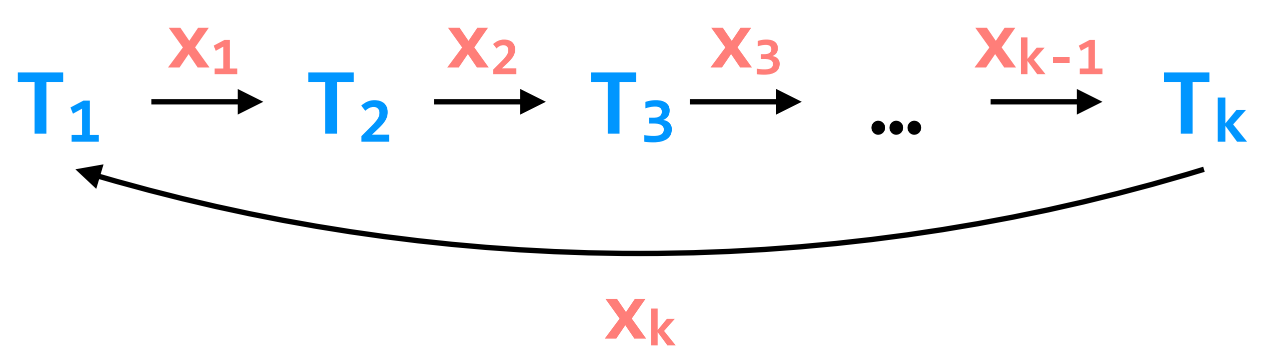

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T_1 **acquires** x_1**.lock**
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T_2 **acquires** x_2**.lock**
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…

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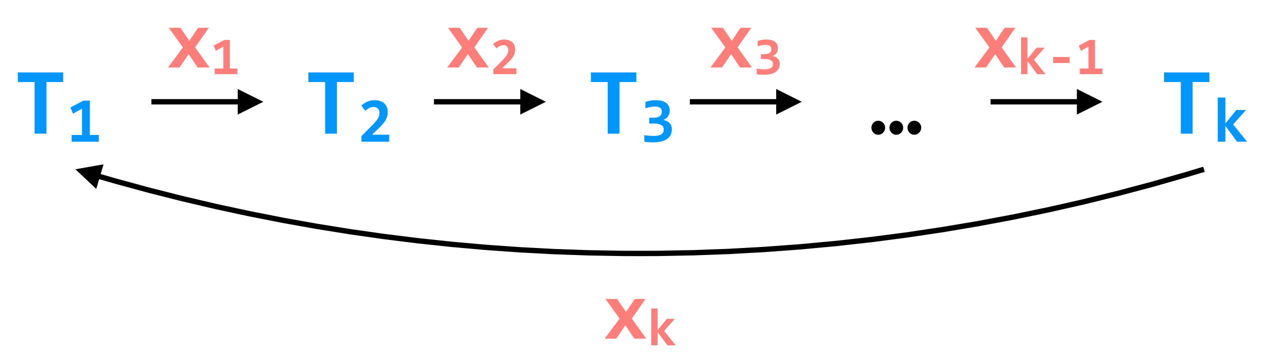

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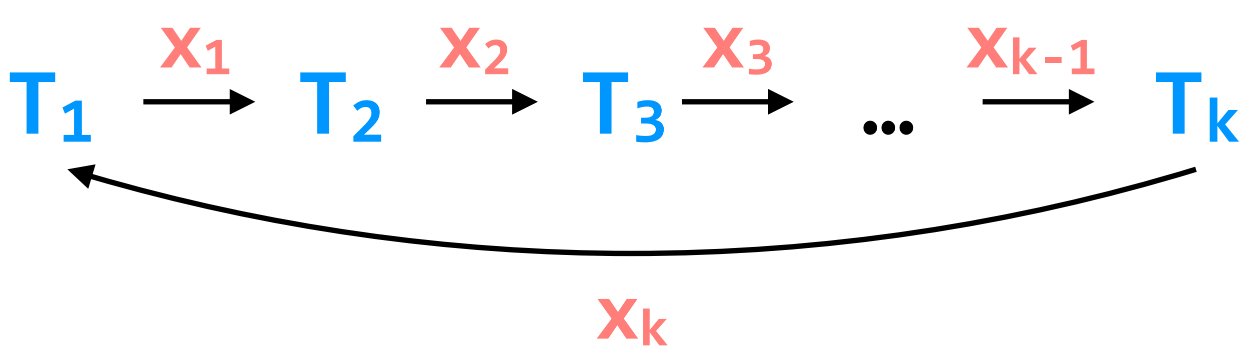

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T1 acquires x1.lock
T1 releases x1.lock
T2 acquires x1.lock

T2 acquires x2.lock
T3 acquires x2.lock

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Tk acquires xk.lock
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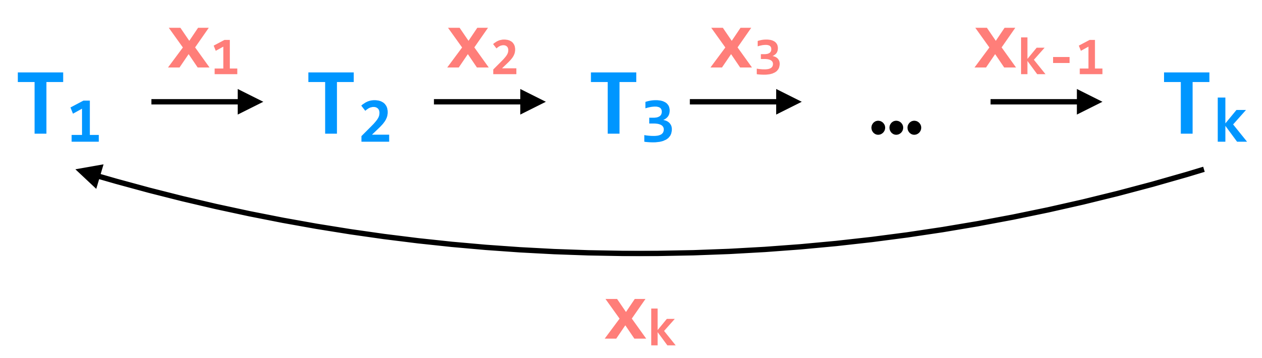

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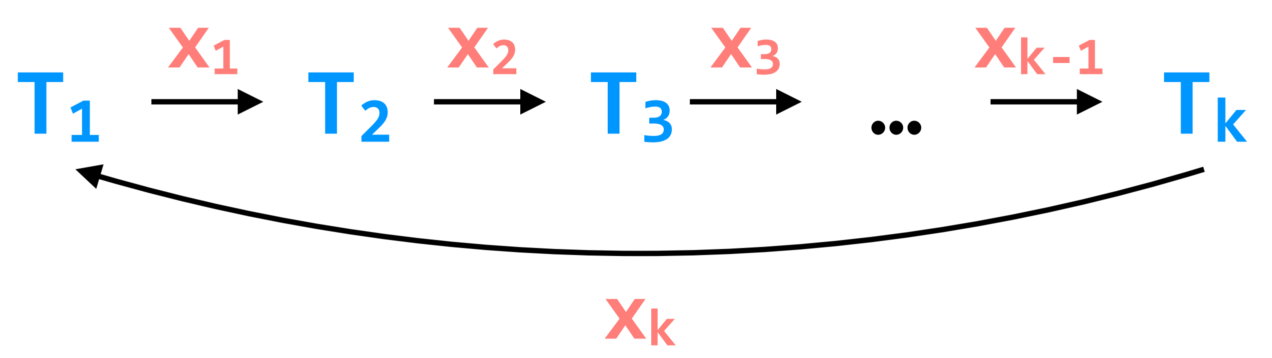

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contradiction: this is not a valid 2PL schedule

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begin
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problem: 2PL can result in deadlock

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for example, suppose T2 wrote to y before x

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for example, suppose T2 wrote to y before x

one solution to this problem is a global ordering on locks; but we hate that! a better solution is to take advantage of atomicity and abort one of the transactions

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two-phase locking (2PL)

with reader-/writer- locks

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problem: performance

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acquire(x.reader_lock)
T1.1 read(x)
acquire(y.reader_lock)
T1.2 tmp = read(y)
acquire(y.writer_lock)
T1.3 write(y, tmp+10)
commit
release(x.reader_lock)
release(y.reader_lock)
release(y.writer_lock)
```

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

two-phase locking (2PL)

with reader-/writer- locks

1. each shared variable has two locks: one for **reading**, one for **writing**

2. before **any** operation on a variable, the transaction must acquire the appropriate lock

3. 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

4. after a transaction releases a lock, it may **not** acquire any other locks

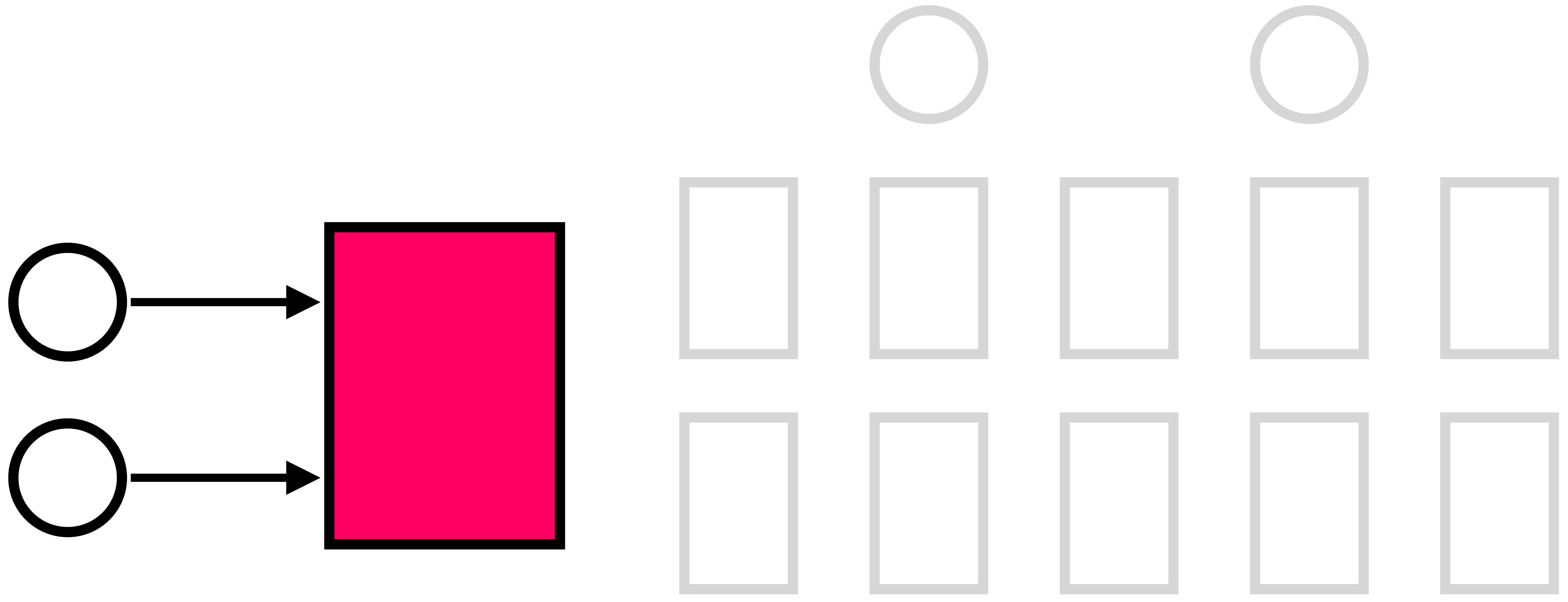
problem: performance

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

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

we will often release reader locks before the commit

our goal is to build **reliable systems from unreliable components**. we want to build systems that serve many clients, store a lot of data, perform well, all while keeping availability high



transactions — which provide **atomicity** and **isolation** — make it easier for us to reason about failures

our job in lecture is to understand how a system *implements* these two abstractions. how do our systems guarantee atomicity? how do they guarantee isolation?

atomicity: provided by **logging**, which gives better performance than shadow copies* at the cost of some added complexity

* shadow copies *are* used in some systems

isolation: provided by **two-phase locking**

different types of **serializability** allow us to specify precise what we want when we run transactions in parallel. **conflict-serializability** is a relatively strict form of serializability.

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

2PL does not produce every possible conflict-serializable schedule — that's okay! the claim is only that the schedules it does produce are conflict-serializable