But that kind of invasive tracking is being scaled back or blocked by Apple and Google to protect people's privacy. Last April, Apple introduced a feature so iPhones users could choose not to be followed by different apps. Google also announced a plan to disable tracking tech in its Chrome web browser by 2023 and said it was working to limit data sharing on Android phones.

Now tracking has shifted to what is known as “first party” tracking. With this method, people are not being trailed from app to app or site to site. But companies are still gathering information on what people are doing on their specific site or app, with users' consent. This kind of tracking, which companies have practiced for years, is growing.
The rise of this tracking has implications for digital advertising, which has depended on user data to know where to aim promotions. It tilts the playing field toward large digital ecosystems such as Google, Snap, TikTok, Amazon and Pinterest, which have millions of their own users and have amassed information on them. Smaller brands have to turn to those platforms if they want to advertise to find new customers.

Many small businesses already appear to be spending less on digital ads that rely on third-party data, such as Facebook and Instagram ads, and are reallocating marketing budgets to platforms with lots of first-party information, like Google and Amazon.

why should “systems people” care about this issue?
Lecture #18: Isolation
what do we want from isolation, and how do we get it?
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.

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

* Shadow copies are used in some systems.
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.

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

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

* shadow copies are used in some systems.
goal: run transactions $T_1, T_2, \ldots, T_N$ concurrently, and have it “appear” as if they ran sequentially.
**goal:** run transactions \( T_1, T_2, \ldots, T_N \) concurrently, and have it “appear” as if they ran sequentially

\[
\begin{align*}
T_1 & \quad \text{begin} \\
T_{1.1} & \quad \text{read}(x) \\
T_{1.2} & \quad \text{tmp} = \text{read}(y) \\
T_{1.3} & \quad \text{write}(y, \text{tmp}+10) \\
\text{commit} & \quad \text{(assume } x, y \text{ initialized to zero)} \\
\end{align*}
\]

\[
\begin{align*}
T_2 & \quad \text{begin} \\
T_{2.1} & \quad \text{write}(x, 20) \\
T_{2.2} & \quad \text{write}(y, 30) \\
\text{commit} & \quad \text{commit} \\
\end{align*}
\]
**goal:** run transactions T1, T2, .., TN concurrently, and have it “appear” as if they ran sequentially

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(assume x, y initialized to zero)

when we run two transactions concurrently, we'll always run the steps of a single transaction in order (e.g., T1.1 before T1.2). but we might interleave steps of T2 in between steps of T1.
**goal:** run transactions $T_1$, $T_2$, .., $T_N$ 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

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(result: x=20; y=30)
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result: x=20; y=40
**goal:** run transactions **T1**, **T2** concurrently, and have it “appear” as if they ran sequentially

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**result:** \(x=20; \, y=40\)
goal: run transactions $T_1$, $T_2$ concurrently, and have it “appear” as if they ran sequentially

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Let’s look at a few different schedules of $T_1$ and $T_2$ (this is not an exhaustive list)

- **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)
  ```

(assume $x$, $y$ initialized to zero)

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

- **T1**
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  begin
  T1.1 read(x)
  T1.2 tmp = read(y)
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result: $x=20$; $y=10$

- **T1**
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**goal:** run transactions **T1, T2** concurrently, and have it “appear” as if they ran sequentially

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

---

**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)
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(assume x, y initialized to zero)

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

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result: x=20; y=40

**T1.1** read(x)
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result: x=20; y=10

**T2.1** write(x, 20)
T2.2 write(y, 30)

---

it seems like the middle schedule is out; x=20; y=10 is not possible in either of our serialized schedules
**goal:** run transactions T1, T2 concurrently, and have it “appear” as if they ran sequentially

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begin
T1.1 read(x)
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(assume x, y initialized to zero)

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<td>T1.2 tmp = read(y)</td>
<td>T2.1 write(x, 20)</td>
</tr>
<tr>
<td>T1.3 write(y, tmp+10)</td>
<td>T2.2 write(y, 30)</td>
</tr>
<tr>
<td>commit</td>
<td>T2.2 write(y, 30)</td>
</tr>
</tbody>
</table>

(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)  
commit
```

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

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

<table>
<thead>
<tr>
<th>T1.1 read(x)</th>
<th>T2.1 write(x, 20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1.2 tmp = read(y)</td>
<td>T2.2 write(y, 30)</td>
</tr>
<tr>
<td>T1.3 write(y, tmp+10)</td>
<td>T2.1 write(x, 20)</td>
</tr>
</tbody>
</table>

**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 $T_1$, $T_2$ concurrently, and have it “appear” as if they ran sequentially

$T_1$
begin
T1.1 read(x)
T1.2 tmp = read(y)
T1.3 write(y, tmp+10)
commit

$T_2$
begin
T2.1 write(x, 20)
T2.2 write(y, 30)
commit

(result: $x=20; y=30$
T1 reads $x=0; y=0$

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

(result: $x=20; y=40$
T1 reads $x=20; y=30$

let’s look at a few different schedules of $T_1$ and $T_2$ (this is not an exhaustive list)

\begin{align*}
&T1.1 \text{ read(x)} \\
&T2.1 \text{ write(x, 20)} \\
&T1.1 \text{ read(x)} \\
&T2.1 \text{ write(x, 20)} \\
&T2.2 \text{ write(y, 30)} \\
&T1.2 \text{ tmp = read(y)} \\
&T2.2 \text{ write(y, 30)} \\
&T1.2 \text{ tmp = read(y)} \\
&T1.3 \text{ write(y, tmp+10)} \\
&T2.1 \text{ write(x, 20)} \\
&T1.3 \text{ write(y, tmp+10)}
\end{align*}

(result: $x=20; y=40$
T1 reads $x=0; y=0$

\begin{align*}
&T1.1 \text{ read(x)} \\
&T2.1 \text{ write(x, 20)} \\
&T1.2 \text{ tmp = read(y)} \\
&T2.1 \text{ write(x, 20)} \\
&T2.2 \text{ write(y, 30)} \\
&T2.2 \text{ write(y, 30)} \\
&T1.2 \text{ tmp = read(y)} \\
&T1.3 \text{ write(y, tmp+10)}
\end{align*}

(result: $x=20; y=10$
T1 reads $x=20; y=30$

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 $y=30$.}

Katrina LaCurts | lacurts@mit.edu | 6.033 2022
**goal:** run transactions T1, T2 concurrently, and have it “appear” as if they ran sequentially

<table>
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<th>T1</th>
<th>T2</th>
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<tbody>
<tr>
<td><strong>begin</strong></td>
<td><strong>begin</strong></td>
</tr>
<tr>
<td>T1.1 read(x)</td>
<td>T2.1 write(x, 20)</td>
</tr>
<tr>
<td>T1.2 tmp = read(y)</td>
<td>T2.1 write(x, 20)</td>
</tr>
<tr>
<td>T1.3 write(y, tmp+10)</td>
<td>T1.2 tmp = read(y)</td>
</tr>
<tr>
<td>commit</td>
<td>T2.2 write(y, 30)</td>
</tr>
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</table>

(assume x, y initialized to zero)

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

<table>
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<td>T1.2 tmp = read(y)</td>
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<td>T1.2 tmp = read(y)</td>
</tr>
<tr>
<td>result: x=20; y=40</td>
<td>T2.2 write(y, 30)</td>
</tr>
<tr>
<td>T1 reads x=0; y=0</td>
<td>T1.1 read(x)</td>
</tr>
<tr>
<td>T2.1 write(x, 20)</td>
<td>T2.1 write(x, 20)</td>
</tr>
<tr>
<td>T2.2 write(y, 30)</td>
<td>T2.2 write(y, 30)</td>
</tr>
<tr>
<td>T1 reads x=20; y=30</td>
<td></td>
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</table>

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 a sequential schedule. **is that okay?**
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

<p>| | |</p>
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<td>begin</td>
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</tr>
<tr>
<td>T1.1 read(x)</td>
<td>T2.1 write(x, 20)</td>
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<td>T2.2 write(y, 30)</td>
</tr>
<tr>
<td>T1.3 write(y, tmp+10)</td>
<td>commit</td>
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</table>

(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

\begin{center}
\begin{tabular}{ll}
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 & \\
\end{tabular}
\end{center}

(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

Assume $x, y$ initialized to zero.

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

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</tr>
<tr>
<td>T1.3 write(y, tmp+10)</td>
<td>commit</td>
</tr>
<tr>
<td>commit</td>
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(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
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)

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

\[
\begin{align*}
T1 & \text{ begin} \\
T1.1 & \text{ read}(x) \\
T1.2 & \text{ tmp = read}(y) \\
T1.3 & \text{ write}(y, \text{ tmp+10}) \\
& \text{ commit} \\
T2 & \text{ begin} \\
T2.1 & \text{ write}(x, 20) \\
T2.2 & \text{ write}(y, 30) \\
& \text{ commit}
\end{align*}
\]

(assume \( x, y \) initialized to zero)

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).

\[
\begin{align*}
T1.1 & \text{ read}(x) \\
T1.2 & \text{ tmp = read}(y) \\
T1.3 & \text{ write}(y, \text{ tmp+10}) \\
T2.1 & \text{ write}(x, 20) \\
T2.2 & \text{ write}(y, 30)
\end{align*}
\]

**order of conflicts**

\[
\begin{align*}
T1.1 & \text{ read}(x) \rightarrow T2.1 \text{ write}(x, 20) \\
T1.2 & \text{ tmp = read}(y) \rightarrow T2.2 \text{ write}(y, 30) \\
T1.3 & \text{ write}(y, \text{ tmp+10}) \rightarrow T2.2 \text{ write}(y, 30)
\end{align*}
\]
**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)

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

\[
\begin{align*}
\text{T1} & \text{ begin} \\
\text{T1.1} & \text{read(x)} \\
\text{T1.2} & \text{tmp = read(y)} \\
\text{T1.3} & \text{write(y, tmp+10)} \\
& \text{commit}
\end{align*}
\]

\[
\begin{align*}
\text{T2} & \text{ begin} \\
\text{T2.1} & \text{write(x, 20)} \\
\text{T2.2} & \text{write(y, 30)} \\
& \text{commit}
\end{align*}
\]

(assume x, y initialized to zero)

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).

order of conflicts
\[
\begin{align*}
\text{T1.1} & \rightarrow \text{T2.1} \\
\text{T1.2} & \rightarrow \text{T2.2} \\
\text{T1.3} & \rightarrow \text{T2.2}
\end{align*}
\]

conflicts
\[
\begin{align*}
\text{T1.1} & \text{ read(x)} \text{ and } \text{T2.1} \text{ write(x, 20)} \\
\text{T1.2} & \text{ tmp = read(y)} \text{ and } \text{T2.2} \text{ write(y, 30)} \\
\text{T1.3} & \text{ write(y, tmp+10)} \text{ and } \text{T2.2} \text{ write(y, 30)}
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conflicts: two operations conflict if they operate on the same object and at least one of them is a write

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T1.1 & \text{ read(x)} \\
T1.2 & \text{ tmp = read(y)} \\
T1.3 & \text{ write(y, tmp+10)} \\
\text{ commit} \\
T2 & \text{ begin} \\
T2.1 & \text{ write(x, 20)} \\
T2.2 & \text{ write(y, 30)} \\
\text{ commit}
\end{align*}
\]

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\[
\begin{align*}
\text{order of conflicts} & \quad \text{order of conflicts} \\
T1.1\text{ read(x)} & \quad T2.1\text{ write(x, 20)} \\
T1.2\text{ tmp = read(y)} & \quad T2.2\text{ write(y, 30)} \\
T1.3\text{ write(y, tmp+10)} & \quad T1.3\text{ write(y, tmp+10)} \\
T2.1\text{ write(x, 20)} & \quad T1.1\text{ read(x)} \\
T2.2\text{ write(y, 30)} & \quad T1.2\text{ tmp = read(y)} \\
T1.3\text{ write(y, tmp+10)} & \quad T1.3\text{ write(y, tmp+10)}
\end{align*}
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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

(assume x, y initialized to zero)

T2

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

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).

order of conflicts
T1.1 -> T2.1
T1.2 -> T2.2
T1.3 -> T2.2

order of conflicts
T2.1 -> T1.1
T2.2 -> T1.2
T1.1 -> T2.1
T1.2 -> T2.2
T1.3 -> 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

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<td>tmp = read(y)</td>
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(assume x, y initialized to zero)

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).

**order of conflicts**

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

**order of conflicts**

| T2.1 write(x, 20) | T2.2 write(y, 30) |
| 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) |
| T2.2 write(y, 30) | 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

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<td><strong>T1.1</strong> read(x) and <strong>T2.1</strong> write(x, 20)</td>
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<td>T2.1 write(x, 20)</td>
<td></td>
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<tr>
<td>T1.2 tmp = read(y)</td>
<td>T1.2 tmp = read(y) and <strong>T2.2</strong> write(y, 30)</td>
<td></td>
</tr>
<tr>
<td>T1.3 write(y, tmp+10)</td>
<td><strong>T1.3</strong> write(y, tmp+10) and <strong>T2.2</strong> write(y, 30)</td>
<td></td>
</tr>
<tr>
<td>commit</td>
<td>commit</td>
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(assume x, y initialized to zero)

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).

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

Assume $x$, $y$ initialized to zero.

**conflicts**

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

(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

\[
\begin{align*}
\text{T1} & \quad \text{T2} \\
\text{begin} & \quad \text{begin} \\
\text{T1.1 read(x)} & \quad \text{T2.1 write(x, 20)} \\
\text{T1.2 tmp = read(y)} & \quad \text{T2.2 write(y, 30)} \\
\text{T1.3 write(y, tmp+10)} & \quad \text{commit} \\
\text{commit} & \quad \\
\end{align*}
\]

(assume x, y initialized to zero)

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).

\[
\begin{align*}
\text{T2.1 write(x, 20)} & \quad \text{order of conflicts} \\
\text{T1.1 read(x)} & \\
\text{T2.2 write(y, 30)} & \\
\text{T1.2 tmp = read(y)} & \\
\text{T1.3 write(y, tmp+10)} & \\
\end{align*}
\]
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
**conflicts**: two operations conflict if they operate on the same object and at least one of them is a write

<table>
<thead>
<tr>
<th>T1</th>
<th>begin</th>
<th>T2</th>
<th>begin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T1.1</td>
<td></td>
<td>T2.1</td>
</tr>
<tr>
<td></td>
<td>read(x)</td>
<td></td>
<td>write(x, 20)</td>
</tr>
<tr>
<td></td>
<td>T1.2</td>
<td></td>
<td>T2.2</td>
</tr>
<tr>
<td></td>
<td>tmp = read(y)</td>
<td></td>
<td>write(y, 30)</td>
</tr>
<tr>
<td></td>
<td>T1.3</td>
<td></td>
<td>T2.2</td>
</tr>
<tr>
<td></td>
<td>write(y, tmp+10)</td>
<td></td>
<td>write(y, 30)</td>
</tr>
<tr>
<td></td>
<td>commit</td>
<td></td>
<td>commit</td>
</tr>
</tbody>
</table>

(assume x, y initialized to zero)

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).

<table>
<thead>
<tr>
<th>T2.1</th>
<th>write(x, 20)</th>
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</thead>
<tbody>
<tr>
<td>T1.1</td>
<td>read(x)</td>
</tr>
<tr>
<td>T2.2</td>
<td>write(y, 30)</td>
</tr>
<tr>
<td>T1.2</td>
<td>tmp = read(y)</td>
</tr>
<tr>
<td>T1.3</td>
<td>write(y, tmp+10)</td>
</tr>
</tbody>
</table>

**order of conflicts**

| 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**

- 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
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)

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) 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.

\[
\begin{align*}
\text{T1} & \quad \text{begin} \\
T1.1 & \quad \text{read}(x) \\
T1.2 & \quad \text{tmp} = \text{read}(y) \\
T1.3 & \quad \text{write}(y, \text{tmp}+10) \\
\text{commit}
\end{align*}
\]

(assume \(x, y\) initialized to zero)

\[
\begin{align*}
\text{T2} & \quad \text{begin} \\
T2.1 & \quad \text{write}(x, 20) \\
T2.2 & \quad \text{write}(y, 30) \\
\text{commit}
\end{align*}
\]

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).

\[
\begin{align*}
\text{T2.1} & \quad \text{write}(x, 20) \\
\text{T1.1} & \quad \text{read}(x) \\
\text{T2.2} & \quad \text{write}(y, 30) \\
\text{T1.2} & \quad \text{tmp} = \text{read}(y) \\
\text{T1.3} & \quad \text{write}(y, \text{tmp}+10)
\end{align*}
\]

**order of conflicts**

\[
\begin{align*}
\text{T2.1} & \rightarrow \text{T1.1} \\
\text{T2.2} & \rightarrow \text{T1.2} \\
\text{T2.2} & \rightarrow \text{T1.3}
\end{align*}
\]

\[
\begin{align*}
\text{T1.1} & \quad \text{read}(x) \\
\text{T2.1} & \quad \text{write}(x, 20) \\
\text{T2.2} & \quad \text{write}(y, 30) \\
\text{T1.2} & \quad \text{tmp} = \text{read}(y) \\
\text{T1.3} & \quad \text{write}(y, \text{tmp}+10)
\end{align*}
\]
**conflicts:** two operations conflict if they operate on the same object and at least one of them is a write

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<th>T1</th>
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<td>read(x)</td>
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<td>T1.1</td>
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<td>write(y, 30)</td>
</tr>
<tr>
<td>T1.2</td>
<td>write(y, tmp+10)</td>
<td>T2.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>commit</td>
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(assume x, y initialized to zero)

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).

<table>
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<tr>
<th>T2.1</th>
<th>write(x, 20)</th>
<th>order of conflicts</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1.1</td>
<td>read(x)</td>
<td>T2.1 -&gt; T1.1</td>
</tr>
<tr>
<td>T2.2</td>
<td>write(y, 30)</td>
<td>T2.2 -&gt; T1.2</td>
</tr>
<tr>
<td>T1.2</td>
<td>tmp = read(y)</td>
<td>T2.2 -&gt; T1.3</td>
</tr>
<tr>
<td>T1.3</td>
<td>write(y, tmp+10)</td>
<td></td>
</tr>
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</table>

order of conflicts

<table>
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<tr>
<th>T1.1</th>
<th>read(x)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1.2</td>
<td>tmp = read(y)</td>
</tr>
<tr>
<td>T1.3</td>
<td>write(y, tmp+10)</td>
</tr>
</tbody>
</table>

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).

order of conflicts

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

order of conflicts

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

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

order of conflicts

T1.1 -> T2.1
T2.2 -> T1.2
T1.3 -> T2.2
**conflicts:** two operations conflict if they operate on the same object and at least one of them is a write

<table>
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<th>T1</th>
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<tr>
<td>begin</td>
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<td>T1.1 read(x)</td>
<td>T2.1 write(x, 20)</td>
</tr>
<tr>
<td>T1.2 tmp = read(y)</td>
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<tr>
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<td>commit</td>
</tr>
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</table>

(commit)

(assume x, y initialized to zero)

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).

<table>
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<tr>
<th>T2.1 write(x, 20)</th>
<th>order of conflicts</th>
<th>T1.1 read(x)</th>
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<tr>
<td>T1.1 read(x)</td>
<td>T2.1 -&gt; T1.1</td>
<td>T2.1 write(x, 20)</td>
<td>T1.1 -&gt; T2.1</td>
</tr>
<tr>
<td>T2.2 write(y, 30)</td>
<td>T2.2 -&gt; T1.2</td>
<td>T2.2 write(y, 30)</td>
<td>T2.2 -&gt; T1.2</td>
</tr>
<tr>
<td>T1.2 tmp = read(y)</td>
<td>T2.2 -&gt; T1.3</td>
<td>T1.2 tmp = read(y)</td>
<td>T1.3 write(y, tmp+10)</td>
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**conflicts:** two operations conflict if they operate on the same object and at least one of them is a write

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<td><strong>begin</strong></td>
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<td>T1.1 read(x)</td>
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</tr>
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</table>

(assume x, y initialized to zero)

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).

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<tr>
<th>T2.1 write(x, 20)</th>
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<th>T1.1 read(x)</th>
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<tbody>
<tr>
<td>T1.1 read(x)</td>
<td>T2.1 -&gt; T1.1</td>
<td>T2.1 write(x, 20)</td>
<td>T1.1 -&gt; T2.1</td>
</tr>
<tr>
<td>T2.2 write(y, 30)</td>
<td>T2.2 -&gt; T1.2</td>
<td>T2.2 write(y, 30)</td>
<td>T2.2 -&gt; T1.2</td>
</tr>
<tr>
<td>T1.2 tmp = read(y)</td>
<td>T2.2 -&gt; T1.3</td>
<td>T1.2 tmp = read(y)</td>
<td></td>
</tr>
<tr>
<td>T1.3 write(y, tmp+10)</td>
<td></td>
<td>T1.3 write(y, tmp+10)</td>
<td></td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
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<th>T1</th>
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<tbody>
<tr>
<td>T1.1</td>
<td>read(x)</td>
</tr>
<tr>
<td>T1.2</td>
<td>tmp = read(y)</td>
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<td>write(y, tmp+10)</td>
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<tr>
<td>commit</td>
<td></td>
</tr>
</tbody>
</table>

(assume x, y initialized to zero)

<table>
<thead>
<tr>
<th>T2</th>
<th>begin</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2.1</td>
<td>write(x, 20)</td>
</tr>
<tr>
<td>T2.2</td>
<td>write(y, 30)</td>
</tr>
<tr>
<td>commit</td>
<td></td>
</tr>
</tbody>
</table>

**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)

**order of conflicts**

- T2.1 -> T1.1
- 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.
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)

**Order of Conflicts**

- **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)**

This schedule is conflict serializable.

**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)**
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.

This schedule is **conflict serializable**

```
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)
T2.3 commit
```

(assume x, y initialized to zero)

This schedule is **not** conflict serializable

```
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)
T2.3 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) |

**Order of conflicts**

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

| T1.2 tmp = read(y) | T2.2 write(y, 30) |
| T2.2 write(y, 30) | T1.2 tmp = read(y) |
| T1.3 write(y, tmp+10) | T2.3 commit |

This schedule is **not** conflict serializable

```
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)
T2.3 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) |

**Order of conflicts**

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

| T1.2 tmp = read(y) | T2.2 write(y, 30) |
| T2.2 write(y, 30) | T1.2 tmp = read(y) |
| T1.3 write(y, tmp+10) | T2.3 commit |

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.

\[
\begin{align*}
\text{T1} & \quad \text{T2} \\
\text{begin} & \quad \text{begin} \\
\text{T1.1 read(x)} & \quad \text{T2.1 write(x, 20)} \\
\text{T1.2 tmp = read(y)} & \quad \text{T2.2 write(y, 30)} \\
\text{T1.3 write(y, tmp+10)} & \quad \text{commit} \\
\text{commit} & \\
\end{align*}
\]

(assume x, y initialized to zero)

\[
\begin{align*}
\text{conflicts} & \\
\text{T1.1 read(x)} & \quad \text{T2.1 write(x, 20)} \\
\text{T1.2 tmp = read(y)} & \quad \text{T2.2 write(y, 30)} \\
\text{T1.3 write(y, tmp+10)} & \quad \text{commit} \\
\end{align*}
\]

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 \( T_i \)

\[
\begin{align*}
\text{order of conflicts} & \\
\text{T2.1 write(x, 20)} & \quad \text{T2.1 \rightarrow T1.1} \\
\text{T1.1 read(x)} & \quad \text{T2.2 \rightarrow T1.2} \\
\text{T2.2 write(y, 30)} & \quad \text{T2.2 \rightarrow T1.3} \\
\text{T1.2 tmp = read(y)} & \\
\text{T1.3 write(y, tmp+10)} & \\
\end{align*}
\]

this schedule is conflict serializable

\[
\begin{align*}
\text{order of conflicts} & \\
\text{T1.1 read(x)} & \quad \text{T1.1 \rightarrow T2.1} \\
\text{T2.1 write(x, 20)} & \quad \text{T2.2 \rightarrow T1.2} \\
\text{T2.2 write(y, 30)} & \quad \text{T1.2 \rightarrow T1.3} \\
\text{T1.2 tmp = read(y)} & \\
\text{T1.3 write(y, tmp+10)} & \\
\end{align*}
\]

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.

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 \( T_i \).

**conflict graph**

\[
\begin{align*}
T2.1 & \text{ write(x, 20)} \\
T1.1 & \text{ read(x)} \\
T2.2 & \text{ write(y, 30)} \\
T1.2 & \text{ tmp = read(y)} \\
T1.3 & \text{ write(y, tmp+10)} \\
\end{align*}
\]

this schedule is conflict serializable

\[
\begin{align*}
T1.1 & \text{ read(x)} \\
T2.1 & \text{ write(x, 20)} \\
T1.2 & \text{ tmp = read(y)} \\
T2.2 & \text{ write(y, 30)} \\
T1.3 & \text{ write(y, tmp+10)} \\
\end{align*}
\]

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)

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

<table>
<thead>
<tr>
<th>T1</th>
<th>T2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>begin</strong></td>
<td><strong>begin</strong></td>
</tr>
<tr>
<td><strong>T1.1</strong></td>
<td><strong>T2.1</strong></td>
</tr>
<tr>
<td>read(x)</td>
<td>write(x, 20)</td>
</tr>
<tr>
<td><strong>T1.2</strong></td>
<td><strong>T2.2</strong></td>
</tr>
<tr>
<td>tmp = read(y)</td>
<td>write(y, 30)</td>
</tr>
<tr>
<td><strong>T1.3</strong></td>
<td></td>
</tr>
<tr>
<td>write(y, tmp+10)</td>
<td>commit</td>
</tr>
<tr>
<td><strong>commit</strong></td>
<td></td>
</tr>
</tbody>
</table>

(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)

(assume x, y initialized to zero)

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)
two-phase locking (2PL)

1. each shared variable has a 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
two-phase locking (2PL)

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3. after a transaction releases a lock, it may not acquire any other locks
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2PL still gives us options for where we place the locks
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

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

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

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

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

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

```
T1
begin
acquire(x.lock)
T1.1 read(x)
acquire(y.lock)
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T1.3 write(y, tmp+10)
release(x.lock)
release(y.lock)
commit
```
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

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

\[
\begin{align*}
T1 & \quad \text{begin} \\
& \quad \text{acquire}(x.\text{lock}) \\
T1.1 & \quad \text{read}(x) \\
& \quad \text{acquire}(y.\text{lock}) \\
& \quad \text{release}(x.\text{lock}) \\
T1.2 & \quad \text{tmp} = \text{read}(y) \\
T1.3 & \quad \text{write}(y, \text{tmp}+10) \\
& \quad \text{release}(y.\text{lock}) \\
& \quad \text{commit}
\end{align*}
\]
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

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

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

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

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

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

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

often we release locks after commit, which is technically strict two-phase locking

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

T1
begin
acquire(x.lock)
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T1.3 write(y, tmp+10)
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release(y.lock)

T2
begin
acquire(x.lock)
T2.1 write(x, 20)
acquire(y.lock)
T2.2 write(y, 30)
commit
release(x.lock)
release(y.lock)
two-phase locking (2PL)

1. each shared variable has a lock

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often we release locks after commit, which is technically strict two-phase locking

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

\begin{itemize}
  \item \textbf{T1}
    \begin{itemize}
    \item begin
    \item acquire(x.lock)
    \item \textbf{T1.1} read(x)
    \item acquire(y.lock)
    \item \textbf{T1.2} tmp = read(y)
    \item \textbf{T1.3} write(y, tmp+10)
    \item commit
    \item release(x.lock)
    \item release(y.lock)
    \end{itemize}
  \end{itemize}

\begin{itemize}
  \item \textbf{T2}
    \begin{itemize}
    \item begin
    \item acquire(x.lock)
    \item \textbf{T2.1} write(x, 20)
    \item acquire(y.lock)
    \item \textbf{T2.2} write(y, 30)
    \item commit
    \item release(x.lock)
    \item release(y.lock)
    \end{itemize}
  \end{itemize}

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)

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

2PL produces a conflict-serializable schedule
(equivalently, 2PL produces a conflict graph without a cycle)
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proof: suppose not. then a cycle exists in the conflict graph
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proof: suppose not. then a cycle exists in the conflict graph

\[ T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow \ldots \rightarrow T_k \]
two-phase locking (2PL)

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\[ T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow \ldots \rightarrow T_k \]

to cause the conflict, each pair of conflicting transactions must have some shared variable that they conflict on
two-phase locking (2PL)

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---

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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

\[ T_1 \xrightarrow{x_1} T_2 \xrightarrow{x_2} T_3 \xrightarrow{x_3} \ldots \xrightarrow{x_{k-1}} T_k \]

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
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

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

![Conflict Graph Diagram](image)

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 $x_1.lock$

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

Katrina LaCurts | lacurts@mit.edu | 6.033 2022
two-phase locking (2PL)

1. each shared variable has a lock

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2PL produces a conflict-serializable schedule
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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

\[
\begin{align*}
T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow \ldots \rightarrow T_k \\
\end{align*}
\]

\[
\begin{align*}
T_1 & \text{ acquires } x_1.lock \\
T_2 & \text{ acquires } x_1.lock \\
T_2 & \text{ acquires } x_2.lock \\
T_3 & \text{ acquires } x_2.lock \\
\end{align*}
\]

In the schedule, each pair of transactions needs to acquire a lock on their shared variable.
two-phase locking (2PL)

1. each shared variable has a lock

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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

in the schedule, each pair of transactions needs to acquire a lock on their shared variable
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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 to cause the conflict, each pair of conflicting **transactions** must have some **shared variable** that they conflict on

```
T1 \rightarrow x_1 \rightarrow T2 \rightarrow x_2 \rightarrow T3 \rightarrow ... \rightarrow x_{k-1} \rightarrow Tk
```

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

```
T1 acquires x_1.lock
T2 acquires x_1.lock
T2 acquires x_2.lock
T3 acquires x_2.lock
...
Tk acquires x_k.lock
T1 acquires x_k.lock
```

in order for the schedule to progress, **T1** must have released its lock on **x_1** before **T2** acquired it
two-phase locking (2PL)

1. each shared variable has a lock

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2PL produces a conflict-serializable schedule
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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

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

\[
T_1 \xrightarrow{x_1} T_2 \xrightarrow{x_2} T_3 \xrightarrow{x_3} \ldots \xrightarrow{x_{k-1}} T_k
\]

\[
T_1 \text{ acquires } x_1.\text{lock}
T_1 \text{ releases } x_1.\text{lock}
T_2 \text{ acquires } x_1.\text{lock}
T_2 \text{ acquires } x_2.\text{lock}
T_3 \text{ acquires } x_2.\text{lock}
\ldots
T_k \text{ acquires } x_k.\text{lock}
T_1 \text{ acquires } x_k.\text{lock}
\]
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
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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

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

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

\[ \begin{align*}
T_1 & \xrightarrow{x_1} T_2 \xrightarrow{x_2} T_3 \xrightarrow{x_3} \ldots \xrightarrow{x_{k-1}} T_k \\
T_1 & \text{acquires } x_1\.lock \\
T_1 & \text{releases } x_1\.lock \\
T_2 & \text{acquires } x_1\.lock \\
T_2 & \text{acquires } x_2\.lock \\
T_3 & \text{acquires } x_2\.lock \\
& \vdots \\
T_k & \text{acquires } x_k\.lock \\
T_1 & \text{acquires } x\.lock \\
\end{align*} \]

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
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

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---

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

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

**problem:** 2PL can result in deadlock

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

T2
begin
    acquire(x.lock)
    T2.1 write(x, 20)
    acquire(y.lock)
    T2.2 write(y, 30)
    commit
    release(x.lock)
    release(y.lock)
```
two-phase locking (2PL)

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T1.3 write(y, tmp+10)
commit
release(x.lock)
release(y.lock)

T2
begin
acquire(y.lock)
T2.1 write(y, 30)
acquire(x.lock)
T2.2 write(x, 20)
commit
release(x.lock)
release(y.lock)
two-phase locking (2PL)

1. each shared variable has a lock

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begin
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T1.3 write(y, tmp+10)
commit
release(x.lock)
release(y.lock)

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

for example, suppose T2 wrote to y before x
**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

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---

**problem:** 2PL can result in deadlock

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

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

---

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
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

T1
begin
acquire(x.lock)
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acquire(y.lock)
T1.2 tmp = read(y)
T1.3 write(y, tmp+10)
commit
release(x.lock)
release(y.lock)

T2
begin
acquire(x.lock)
T2.1 write(x, 20)
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T2.2 write(y, 30)
commit
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**two-phase locking (2PL)**

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---

**problem:** performance

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

T2
begin
acquire(x.lock)
T2.1 write(x, 20)
acquire(y.lock)
T2.2 write(y, 30)
commit
release(x.lock)
release(y.lock)
**two-phase locking (2PL)**
with reader-/writer- locks

**problem:** performance

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

T2
begin
acquire(x.lock)
T2.1 write(x, 20)
acquire(y.lock)
T2.2 write(y, 30)
commit
release(x.lock)
release(y.lock)
```
two-phase locking (2PL)

with reader-/writer- locks

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

   \[
   \begin{align*}
   &T1 \\
   &\text{begin} \\
   &\text{acquire}(x.\text{lock}) \\
   &T1.1 \ \text{read}(x) \\
   &\text{acquire}(y.\text{lock}) \\
   &T1.2 \ \text{tmp} = \text{read}(y) \\
   &T1.3 \ \text{write}(y, \text{tmp}+10) \\
   &\text{commit} \\
   &\text{release}(x.\text{lock}) \\
   &\text{release}(y.\text{lock})
   \end{align*}
   \]

   \[
   \begin{align*}
   &T2 \\
   &\text{begin} \\
   &\text{acquire}(x.\text{lock}) \\
   &T2.1 \ \text{write}(x, 20) \\
   &\text{acquire}(y.\text{lock}) \\
   &T2.2 \ \text{write}(y, 30) \\
   &\text{commit} \\
   &\text{release}(x.\text{lock}) \\
   &\text{release}(y.\text{lock})
   \end{align*}
   \]

problem: performance
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

**problem: performance**

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

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

**problem: performance**

```
T1
begin
acquire(x.lock)
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acquire(x.lock)
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release(x.lock)
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```
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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

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begin
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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

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)
two-phase locking (2PL) with reader-/writer- locks

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**problem:** performance

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we will often release reader locks before the commit
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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