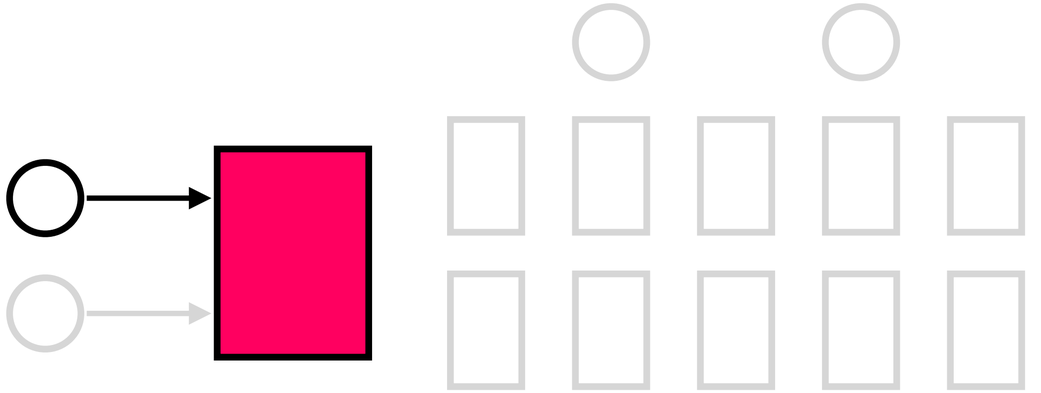
6.1800 Spring 2025

Lecture #17: Atomicity via Logging

superior to shadow copies in almost every way

Katrina LaCurts | lacurts@mit.edu | 6.1800 2025

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?

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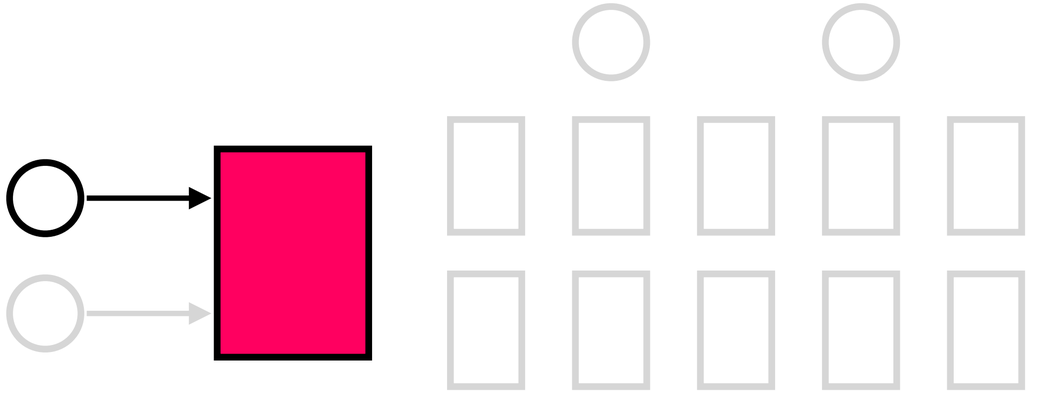

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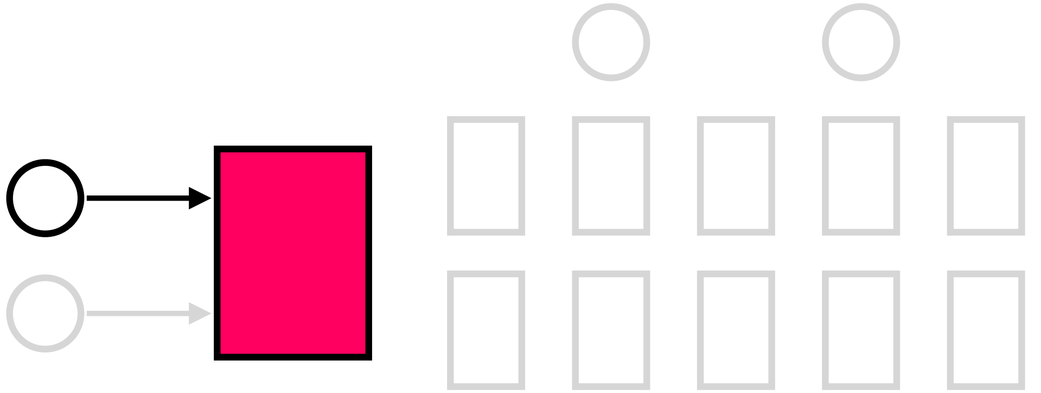

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isolation: we don't really have this yet
(coarse-grained locks perform poorly; fine-grained locks are difficult to reason about)

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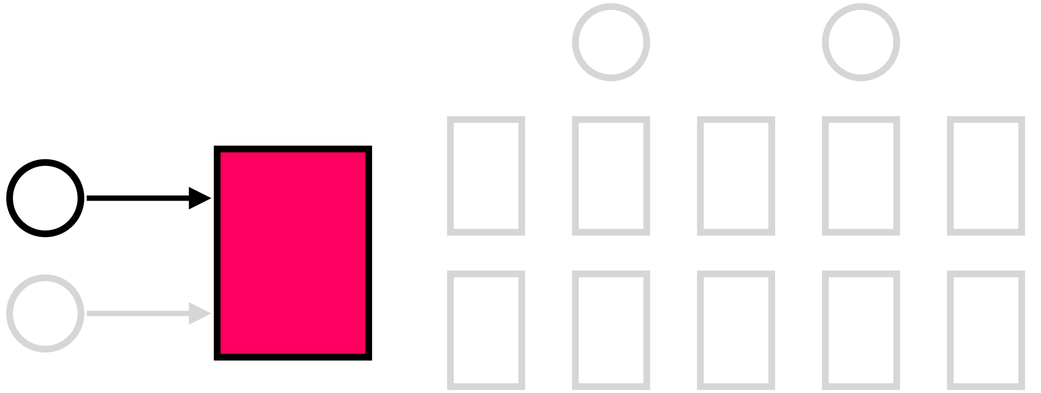

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our job in lecture is to understand how a system *implements* these two abstractions.
how do our systems guarantee atomicity? how do they guarantee isolation?

atomicity: logging, which is going to provide us with much better performance 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)

```
transfer (bank, account_a, account_b, amount):
    bank[account_a] = bank[account_a] - amount
    bank[account_b] = bank[account_b] + amount
```

this was our starting bank transfer code from last week.
let's put it into **transaction** syntax.

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this was our starting bank transfer code from last week. let's put it into **transaction** syntax.

```
begin
A_local = read(A)
B_local = read(B)
write(A, A_local-amount)
write(B, B_local+amount)
commit
```

```
transfer (bank, account_a, account_b, amount):
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write(A, read(A)-amount)
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we can even be more succinct and get rid of the local variables

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write(A, read(A)-amount)
write(B, read(B)+amount)
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we can even be more succinct and get rid of the local variables

to broaden our horizons, we're going to move away from bank transfers and think about generic reads/writes

```
begin    // T1
write(A, 100)
write(B, 50)
commit   // A=100; B=50

begin    // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit   // A=80; B=70

begin    // T3
write(A, read(A)+30)
commit   // A=110; B=70
```

our goal today is to make sure that each transaction in a series (such as the one below) is atomic *and* that our system has good performance

remember that one problem with shadow copies is that they rewrite an entire file even for small changes

```
begin    // T1
write(A, 100)
write(B, 50)
commit   // A=100; B=50

begin    // T2
write(A, read(A)-20)
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```

crash! 💥

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commit   // A=80; B=70

begin    // T3
write(A, read(A)+30)
```

crash! 💥

problem: after crash, `A=110`,
but `T3` never committed

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commit    // A=80; B=70

begin     // T3
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```

crash! 💥

problem: after crash, `A=110`, but `T3` never committed

we need a way to revert to **A**'s previous committed value

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

```
begin    // T1
write(A, 100)
write(B, 50)
commit   // A=100; B=50

begin    // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit   // A=80; B=70

begin    // T3
write(A, read(A)+30)
```

TID	T1	T1	T1	T2	T2	T2	T3	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE	ABORT
OLD	A=0	B=0		A=100	B=50		A=80	
NEW	A=100	B=50		A=80	B=70		A=110	

```
begin    // T1
write(A, 100)
write(B, 50)
commit   // A=100; B=50

begin    // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit   // A=80; B=70

begin    // T3
write(A, read(A)+30)
if read(B) < 100:
  abort
else
  commit
```

brief interlude: we're going to change this example slightly, to illustrate one additional point

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
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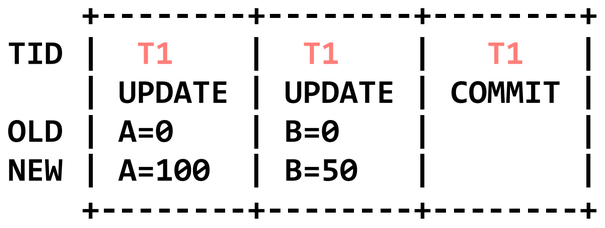


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TID	T1	T1	T1
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OLD	A=0	B=0	
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let's try to read the value of A from this log

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	UPDATE	UPDATE	COMMIT
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read(log, var):
  commits = []
  // scan backwards
  for record r in log[len(log) - 1] .. log[0]:
    // keep track of commits
    if r.type == COMMIT:
      commits.add(r.tid)
    // find var's last committed value
    elif r.type == UPDATE and
      r.tid in commits and r.var == var:
        return r.new_value
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TID	T1	T1	T1
	UPDATE	UPDATE	COMMIT
OLD	A=0	B=0	
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```
commits = [T1]
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TID	T1	T1	T1	T2	T2	T2	T3
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```

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

begin     // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

now back to our original example

let's try to read the value of A from this log

```
read(log, var):
  commits = []
  // scan backwards
  for record r in log[len(log) - 1] .. log[0]:
    // keep track of commits
    if r.type == COMMIT:
      commits.add(r.tid)
    // find var's last committed value
    elif r.type == UPDATE and
      (r.tid in commits or r.tid == current_tid)
      and r.var == var:
        return r.new_value
```

after a crash, the log is still correct; uncommitted updates will not be read

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

```
begin    // T1
write(A, 100)
write(B, 50)
commit   // A=100; B=50

begin    // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit   // A=80; B=70

begin    // T3
write(A, read(A)+30)
```

crash! 💥

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

```
begin    // T1
write(A, 100)
write(B, 50)
commit   // A=100; B=50

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write(A, read(A)-20)
write(B, read(B)+20)
commit   // A=80; B=70

begin    // T3
write(A, read(A)+30)
crash! 💥
```

writes contain the old and new value of a variable. each write is a small append to the end of the log

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

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begin    // T1
write(A, 100)
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crash! 💥
```

writes contain the old and new value of a variable. each write is a small append to the end of the log

to **read** a variable *x*, the system scans backwards through the log to find *x*'s last committed value

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

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begin     // T1
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crash! 💥
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writes contain the old and new value of a variable. each write is a small append to the end of the log

to **read** a variable *x*, the system scans backwards through the log to find *x*'s last committed value

the **commit point** for a transaction is writing the **`COMMIT`** record

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

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begin     // T1
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write(A, read(A)+30)
crash! 💥
```

writes contain the old and new value of a variable. each write is a small append to the end of the log

to **read** a variable *x*, the system scans backwards through the log to find *x*'s last committed value

the **commit point** for a transaction is writing the **`COMMIT`** record

problem: reads can be very slow

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

```
begin     // T1
write(A, 100)
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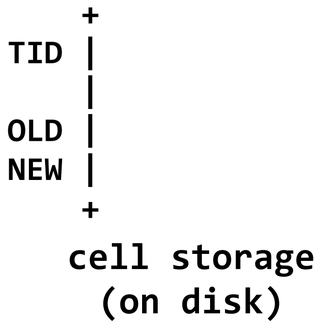
write(A, read(A)+30)
crash! 💥
```

```
read(log, var):
  commits = []
  // scan backwards
  for record r in log[len(log) - 1] .. log[0]:
    // keep track of commits
    if r.type == COMMIT:
      commits.add(r.tid)
    // find var's last committed value
    elif r.type == UPDATE and
      (r.tid in commits or r.tid == current_tid)
      and r.var == var:
        return r.new_value
```

problem: reads can be very slow




```
begin    // T1
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commit   // A=100; B=50

begin    // T2
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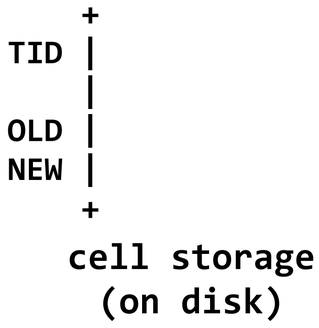


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commit   // A=100; B=50

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write(A, read(A)-20)
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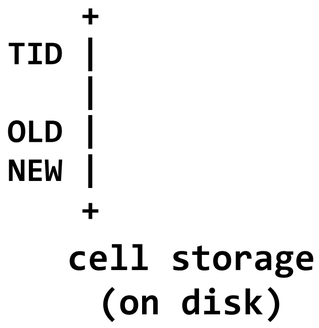
begin    // T3
write(A, read(A)+30)
```

```
read(var):
  return cell_read(var)


write(var, value):
  log.append(current_tid, “UPDATE”, var,
             read(var), value)
  cell_write(var, value)
```

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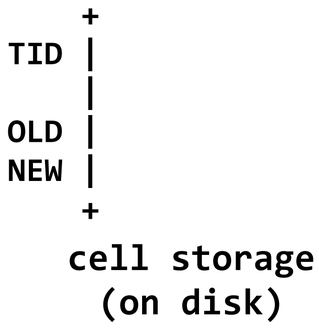


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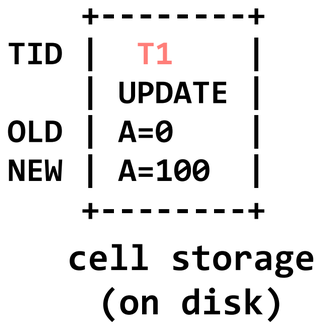


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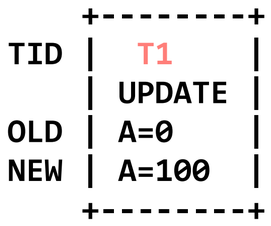

cell storage
(on disk)

A 100

```
begin     // T1
write(A, 100)
write(B, 50)
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write(var, value):
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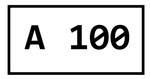
```

```
    +--------+
TID |  T1    |
    | UPDATE |
OLD | A=0    |
NEW | A=100  |
    +--------+
```

cell storage (on disk)

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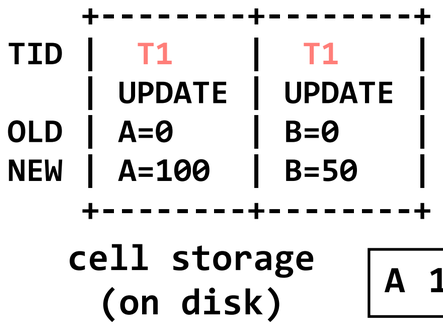


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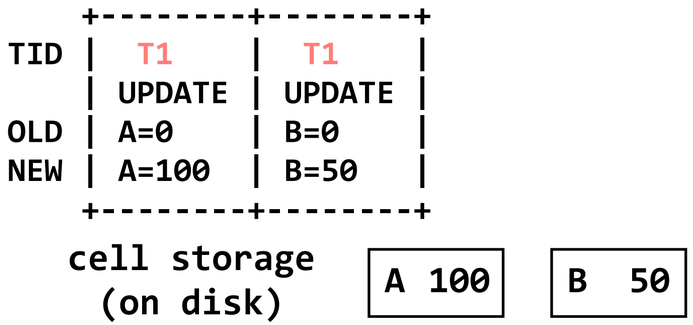


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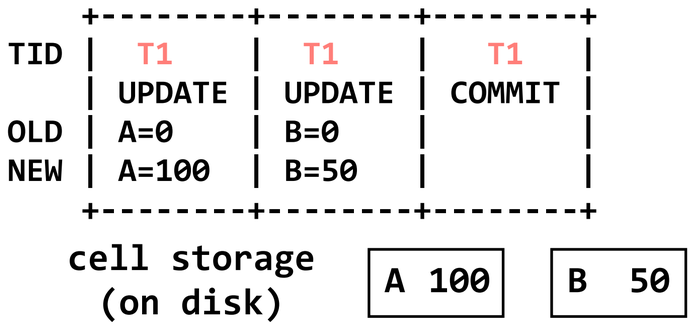


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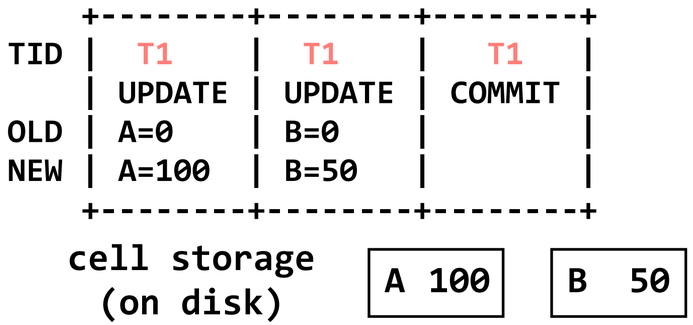


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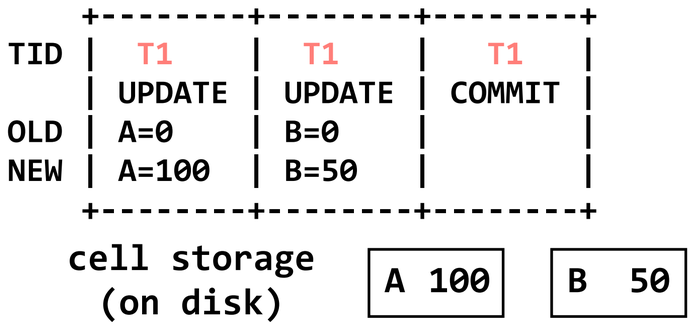


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read(var):
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```
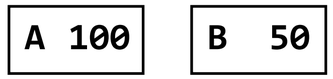

TID	T1	T1	T1	T2
	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100
NEW	A=100	B=50		A=80

cell storage (on disk)

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TID	T1	T1	T1	T2
	UPDATE	UPDATE	COMMIT	UPDATE
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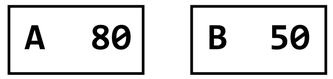
NEW	A=100	B=50		A=80

cell storage (on disk)

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write(B, 50)
commit    // A=100; B=50

begin     // T2
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TID	T1	T1	T1	T2
	UPDATE	UPDATE	COMMIT	UPDATE
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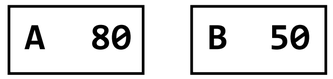
NEW	A=100	B=50		A=80

cell storage (on disk)

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TID	T1	T1	T1	T2	T2
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE
OLD	A=0	B=0		A=100	B=50
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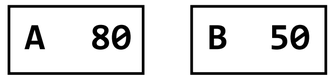
cell storage (on disk)

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TID	T1	T1	T1	T2	T2
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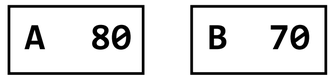
cell storage (on disk)

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TID	T1	T1	T1	T2	T2	T2
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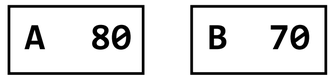
cell storage (on disk)

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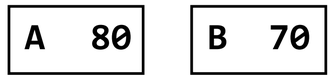
TID	T1	T1	T1	T2	T2	T2
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT
OLD	A=0	B=0		A=100	B=50	
NEW	A=100	B=50		A=80	B=70	

cell storage (on disk)

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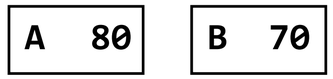
read(var):
  return cell_read(var)


write(var, value):
  log.append(current_tid, “UPDATE”, var,
                read(var), value)
  cell_write(var, value)
```

TID	T1	T1	T1	T2	T2	T2
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT
OLD	A=0	B=0		A=100	B=50	
NEW	A=100	B=50		A=80	B=70	

cell storage (on disk)




```
begin    // T1
write(A, 100)
write(B, 50)
commit   // A=100; B=50

begin    // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit   // A=80; B=70

begin    // T3
write(A, read(A)+30)
```

```
read(var):
  return cell_read(var)


write(var, value):
  log.append(current_tid, “UPDATE”, var,
                read(var), value)
  cell_write(var, value)
```

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110


```
begin    // T1
write(A, 100)
write(B, 50)
commit   // A=100; B=50

begin    // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit   // A=80; B=70

begin    // T3
write(A, read(A)+30)
```

```
read(var):
  return cell_read(var)


write(var, value):
  log.append(current_tid, “UPDATE”, var,
                read(var), value)
  cell_write(var, value)
```

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110


```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

begin     // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
```

```
read(var):
  return cell_read(var)


write(var, value):
  log.append(current_tid, “UPDATE”, var,
                read(var), value)
  cell_write(var, value)
```

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110


```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

begin     // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

```
read(var):
  return cell_read(var)


write(var, value):
  log.append(current_tid, “UPDATE”, var,
                read(var), value)
  cell_write(var, value)
```

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

cell storage (on disk) | A 110 | B 70 |

```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

begin     // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

problem: the value of A in cell storage never committed (and so should not be read after recovery); we need to repair cell storage

```
read(var):
  return cell_read(var)


write(var, value):
  log.append(current_tid, “UPDATE”, var,
                read(var), value)
  cell_write(var, value)
```

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110


```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

begin     // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

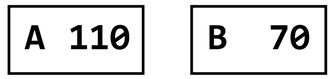
```
read(var):
  return cell_read(var)


write(var, value):
  log.append(current_tid, “UPDATE”, var,
             read(var), value)
  cell_write(var, value)


recover(log):
  commits = []
  for record r in log[len(log)-1] .. log[0]:
    if r.type == COMMIT:
      commits.add(r.tid)
    if r.type == UPDATE and r.tid not in commits:
      cell_write(r.var, r.old_val) // undo
```

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

cell storage (on disk)




```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

begin     // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

```
read(var):
  return cell_read(var)


write(var, value):
  log.append(current_tid, “UPDATE”, var,
             read(var), value)
  cell_write(var, value)


recover(log):
  commits = []
  for record r in log[len(log)-1] .. log[0]:
    if r.type == COMMIT:
      commits.add(r.tid)
    if r.type == UPDATE and r.tid not in commits:
      cell_write(r.var, r.old_val) // undo


commits = []
```

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110


```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

begin     // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

```
read(var):
  return cell_read(var)

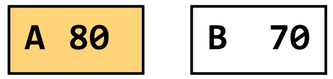

write(var, value):
  log.append(current_tid, “UPDATE”, var,
             read(var), value)
  cell_write(var, value)


recover(log):
  commits = []
  for record r in log[len(log)-1] .. log[0]:
    if r.type == COMMIT:
      commits.add(r.tid)
    if r.type == UPDATE and r.tid not in commits:
      cell_write(r.var, r.old_val) // undo


commits = []
```

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

cell storage (on disk)




```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

begin     // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

```
read(var):
  return cell_read(var)

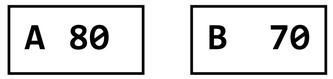

write(var, value):
  log.append(current_tid, “UPDATE”, var,
             read(var), value)
  cell_write(var, value)


recover(log):
  commits = []
  for record r in log[len(log)-1] .. log[0]:
    if r.type == COMMIT:
      commits.add(r.tid)
    if r.type == UPDATE and r.tid not in commits:
      cell_write(r.var, r.old_val) // undo


commits = []
```

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

cell storage (on disk)




```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

begin     // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

```
read(var):
  return cell_read(var)

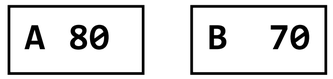

write(var, value):
  log.append(current_tid, “UPDATE”, var,
             read(var), value)
  cell_write(var, value)


recover(log):
  commits = []
  for record r in log[len(log)-1] .. log[0]:
    if r.type == COMMIT:
      commits.add(r.tid)
    if r.type == UPDATE and r.tid not in commits:
      cell_write(r.var, r.old_val) // undo


commits = []
```

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

cell storage (on disk)




```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

begin     // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

```
read(var):
  return cell_read(var)

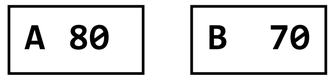

write(var, value):
  log.append(current_tid, “UPDATE”, var,
                read(var), value)
  cell_write(var, value)


recover(log):
  commits = []
  for record r in log[len(log)-1] .. log[0]:
    if r.type == COMMIT:
      commits.add(r.tid)
    if r.type == UPDATE and r.tid not in commits:
      cell_write(r.var, r.old_val) // undo
```

```
commits = [T2]
```

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

cell storage (on disk)




```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

begin     // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

```
read(var):
  return cell_read(var)


write(var, value):
  log.append(current_tid, “UPDATE”, var,
             read(var), value)
  cell_write(var, value)


recover(log):
  commits = []
  for record r in log[len(log)-1] .. log[0]:
    if r.type == COMMIT:
      commits.add(r.tid)
    if r.type == UPDATE and r.tid not in commits:
      cell_write(r.var, r.old_val) // undo
```

commits = [T2]

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

cell storage (on disk) | A 80 | | B 70 |

```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

begin     // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

```
read(var):
  return cell_read(var)

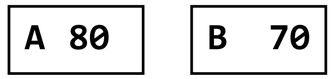

write(var, value):
  log.append(current_tid, “UPDATE”, var,
             read(var), value)
  cell_write(var, value)


recover(log):
  commits = []
  for record r in log[len(log)-1] .. log[0]:
    if r.type == COMMIT:
      commits.add(r.tid)
    if r.type == UPDATE and r.tid not in commits:
      cell_write(r.var, r.old_val) // undo
```

commits = [T2]

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

cell storage (on disk)




```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

begin     // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

```
read(var):
  return cell_read(var)

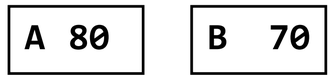

write(var, value):
  log.append(current_tid, “UPDATE”, var,
             read(var), value)
  cell_write(var, value)


recover(log):
  commits = []
  for record r in log[len(log)-1] .. log[0]:
    if r.type == COMMIT:
      commits.add(r.tid)
    if r.type == UPDATE and r.tid not in commits:
      cell_write(r.var, r.old_val) // undo
```

commits = [T2]

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

cell storage (on disk)




```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

begin     // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

```
read(var):
  return cell_read(var)

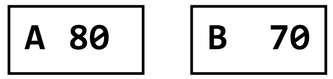

write(var, value):
  log.append(current_tid, “UPDATE”, var,
             read(var), value)
  cell_write(var, value)


recover(log):
  commits = []
  for record r in log[len(log)-1] .. log[0]:
    if r.type == COMMIT:
      commits.add(r.tid)
    if r.type == UPDATE and r.tid not in commits:
      cell_write(r.var, r.old_val) // undo
```

```
commits = [T2, T1]
```

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

cell storage (on disk)




```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

begin     // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

```
read(var):
  return cell_read(var)

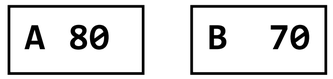

write(var, value):
  log.append(current_tid, “UPDATE”, var,
             read(var), value)
  cell_write(var, value)


recover(log):
  commits = []
  for record r in log[len(log)-1] .. log[0]:
    if r.type == COMMIT:
      commits.add(r.tid)
    if r.type == UPDATE and r.tid not in commits:
      cell_write(r.var, r.old_val) // undo
```

commits = [T2, T1]

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

cell storage (on disk)




```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

begin     // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

```
read(var):
  return cell_read(var)


write(var, value):
  log.append(current_tid, “UPDATE”, var,
             read(var), value)
  cell_write(var, value)


recover(log):
  commits = []
  for record r in log[len(log)-1] .. log[0]:
    if r.type == COMMIT:
      commits.add(r.tid)
    if r.type == UPDATE and r.tid not in commits:
      cell_write(r.var, r.old_val) // undo
```

```
commits = [T2, T1]
```

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110


```
begin    // T1
write(A, 100)
write(B, 50)
commit   // A=100; B=50

begin    // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit   // A=80; B=70

begin    // T3
write(A, read(A)+30)
```

crash! 💥

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110


```
begin    // T1
write(A, 100)
write(B, 50)
commit   // A=100; B=50

begin    // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit   // A=80; B=70

begin    // T3
write(A, read(A)+30)
crash! 💥
```

writes go to the log first and then cell storage.

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

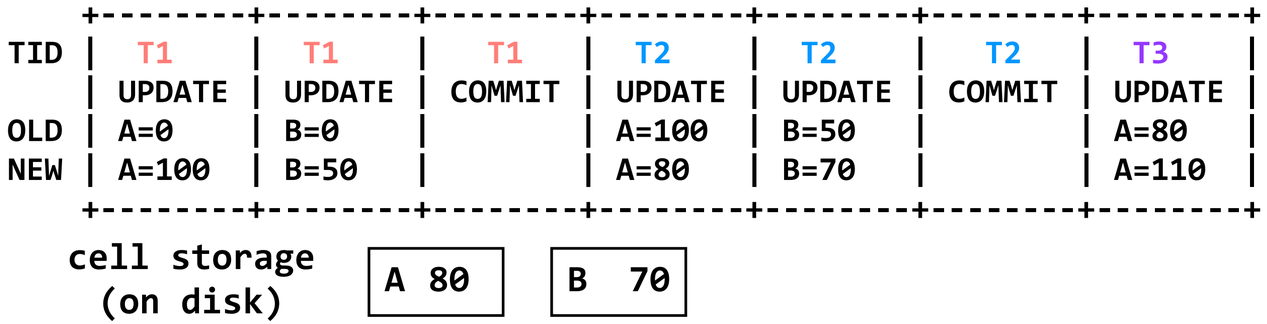

```
begin    // T1
write(A, 100)
write(B, 50)
commit   // A=100; B=50

begin    // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit   // A=80; B=70

begin    // T3
write(A, read(A)+30)
crash! 💥
```

writes go to the log first and then cell storage.

to **read** a variable *x*, the system reads *x*'s value from cell storage




```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

begin     // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

writes go to the log first and then cell storage.

to **read** a variable *x*, the system reads *x*'s value from cell storage

on **recovery**, the system must repair cell storage by undo-ing any uncommitted transactions

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

cell storage (on disk) | A 80 | | B 70 |

```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

begin     // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

writes go to the log first and then cell storage.

to **read** a variable *x*, the system reads *x*'s value from cell storage

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problem: read performance is now great, but writes got slower

(recovery also got slower; we'll come to that)

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110


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begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

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write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

```
read(var):
  return cell_read(var)


write(var, value):
  log.append(current_tid, “UPDATE”, var,
             read(var), value)
  cell_write(var, value)


recover(log):
  commits = []
  for record r in log[len(log)-1] .. log[0]:
    if r.type == COMMIT:
      commits.add(r.tid)
    if r.type == UPDATE and r.tid not in commits:
      cell_write(r.var, r.old_val) // undo
```

problem: read performance is now great, but writes got slower

(recovery also got slower; we’ll come to that)

cell storage (on disk)

cache (memory)

```
begin    // T1
write(A, 100)
write(B, 50)
commit   // A=100; B=50

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write(B, read(B)+20)
commit   // A=80; B=70

begin    // T3
write(A, read(A)+30)
```

```
read(var):
  if var in cache:
    return cache[var]
  else:
    // may evict others from cache to cell storage
    cache[var] = cell_read(var)
    return cache[var]

write(var, value):
  log.append(current_tid, update, var,
             read(var), value)
  cache[var] = value

flush(): // called “occasionally”
  cell_write(var, cache[var]) for each var
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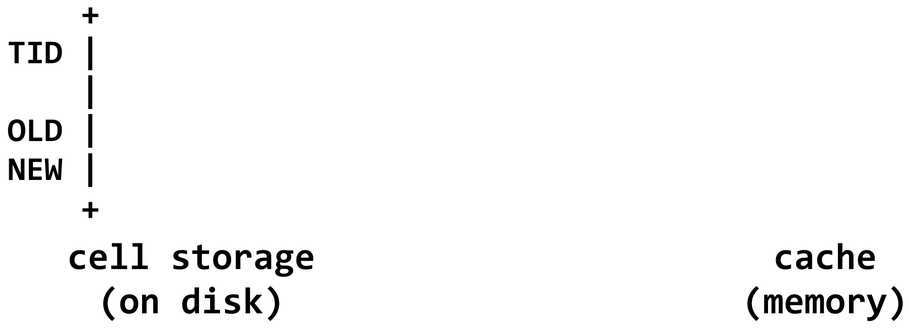


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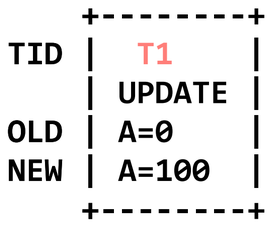

cell storage (on disk)

cache (memory)

```
begin    // T1
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commit   // A=100; B=50

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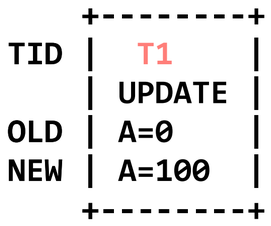

cell storage
(on disk)

cache
(memory) A 100

```
begin    // T1
write(A, 100)
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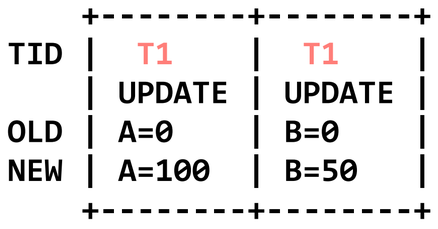

cell storage
(on disk)

cache
(memory)


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begin    // T1
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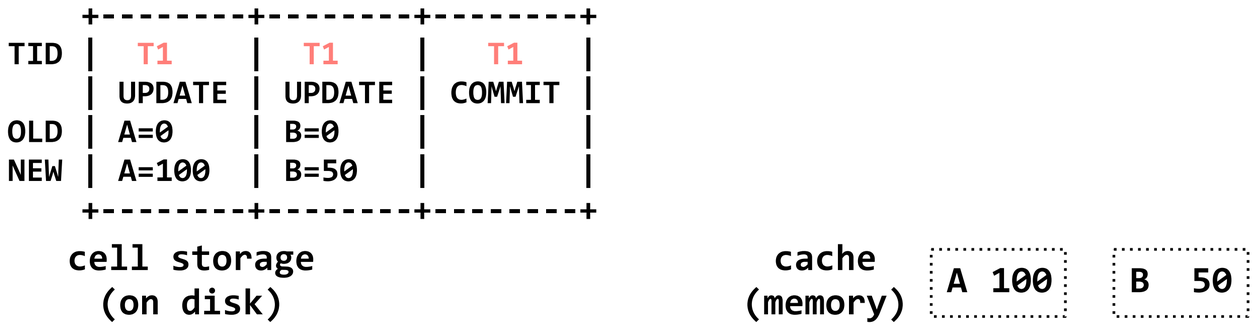


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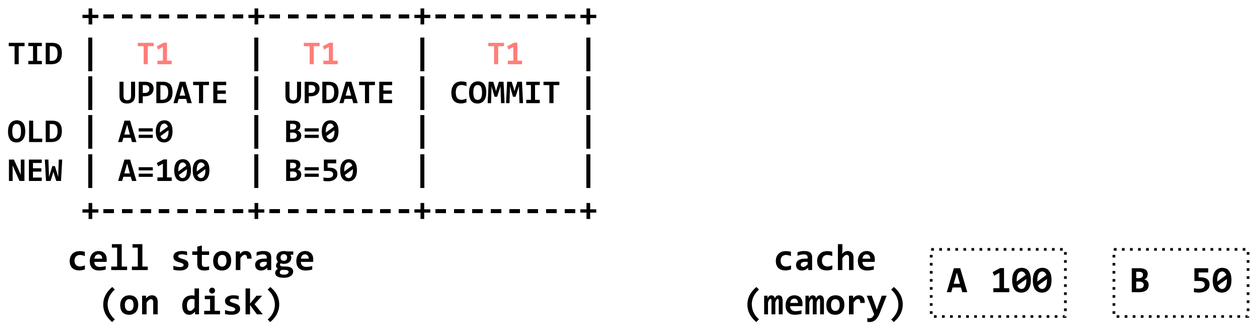


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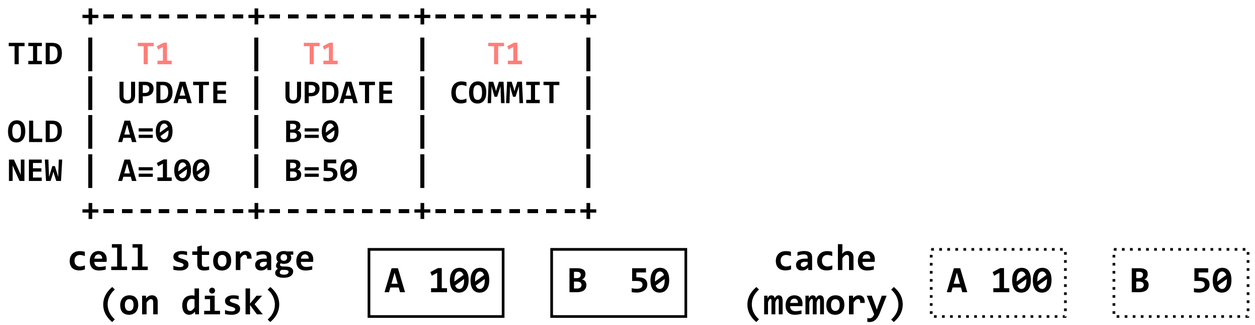


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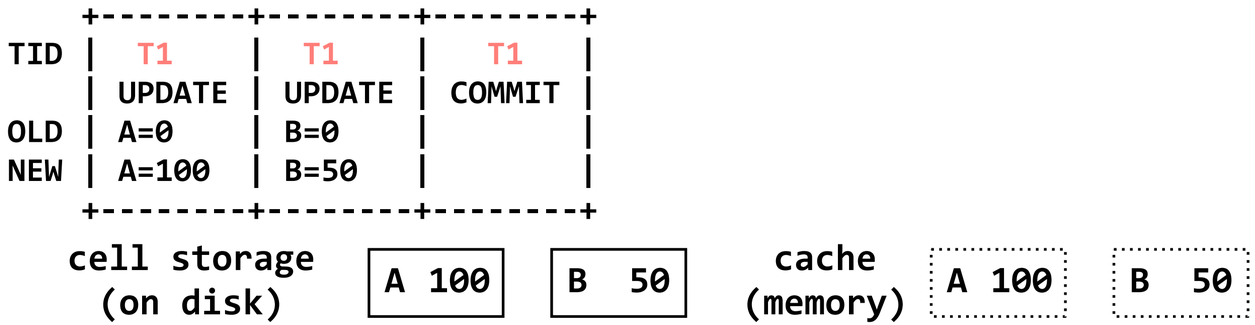


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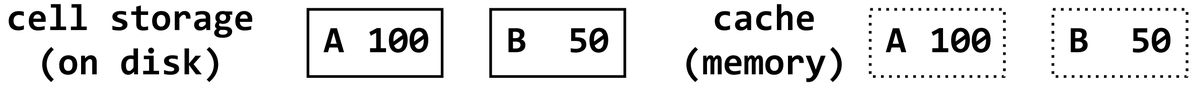
TID	T1	T1	T1	T2
	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100
NEW	A=100	B=50		A=80

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TID	T1	T1	T1	T2
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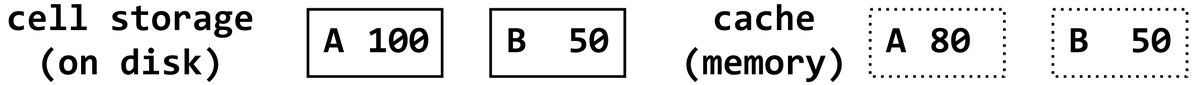


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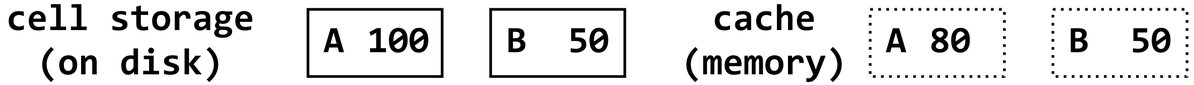


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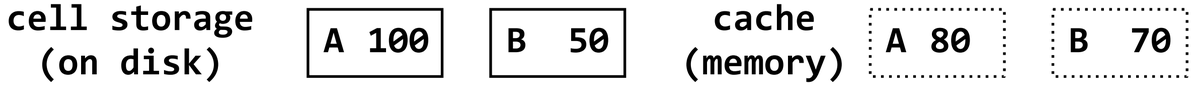


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	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT
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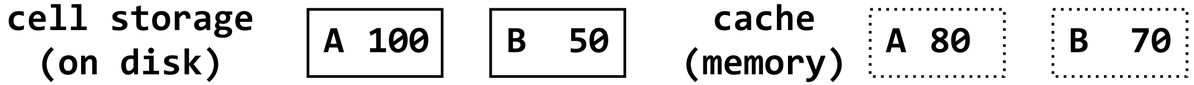


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TID	T1 UPDATE	T1 UPDATE	T1 COMMIT	T2 UPDATE	T2 UPDATE	T2 COMMIT
OLD	A=0	B=0		A=100	B=50	
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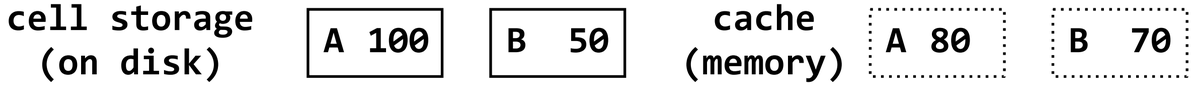


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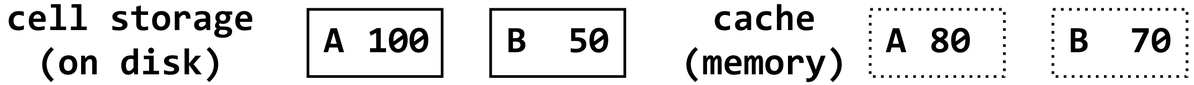


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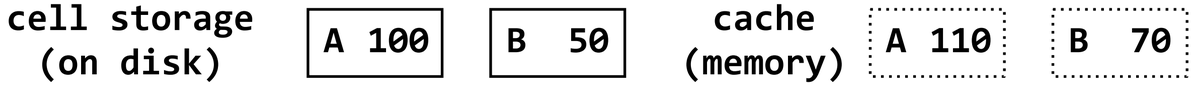


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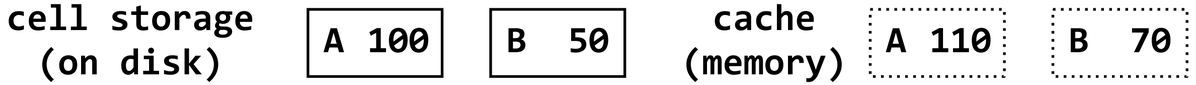
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110




```
begin    // T1
write(A, 100)
write(B, 50)
commit   // A=100; B=50
flush()

begin    // T2
write(A, read(A)-20)
write(B, read(B)+20)
commit   // A=80; B=70

begin    // T3
write(A, read(A)+30)
```

```
read(var):
  if var in cache:
    return cache[var]
  else:
    // may evict others from cache to cell storage
    cache[var] = cell_read(var)
    return cache[var]

write(var, value):
  log.append(current_tid, update, var,
             read(var), value)
  cache[var] = value

flush(): // called “occasionally”
  cell_write(var, cache[var]) for each var
```

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
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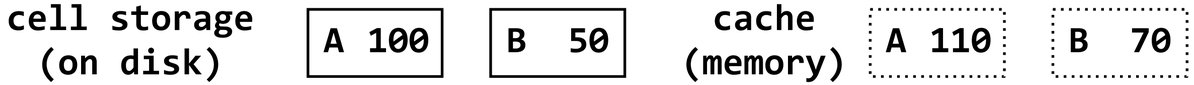


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begin     // T1
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write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

```
read(var):
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    return cache[var]

write(var, value):
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             read(var), value)
  cache[var] = value

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TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
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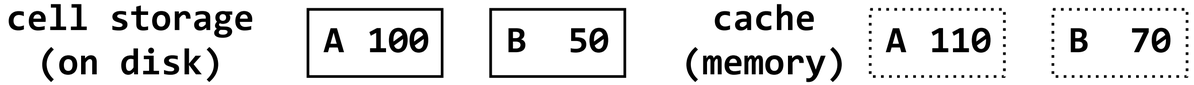


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begin    // T3
write(A, read(A)+30)
crash! 💥
```

on a crash, all values in the cache go away
(because they're in memory, and memory is volatile)

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  log.append(current_tid, update, var,
             read(var), value)
  cache[var] = value

flush(): // called "occasionally"
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TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
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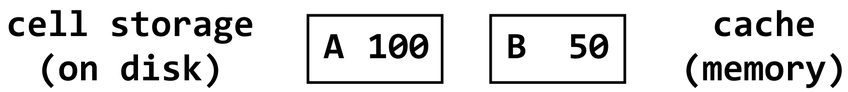


```
begin    // T1
write(A, 100)
write(B, 50)
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write(var, value):
  log.append(current_tid, update, var,
             read(var), value)
  cache[var] = value

flush(): // called "occasionally"
  cell_write(var, cache[var]) for each var
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TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110


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begin     // T1
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write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
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```

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    cache[var] = cell_read(var)
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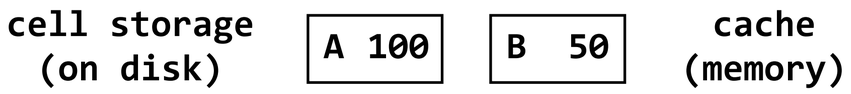
write(var, value):
  log.append(current_tid, update, var,
             read(var), value)
  cache[var] = value

flush(): // called "occasionally"
  cell_write(var, cache[var]) for each var
```

question: what needs to be repaired during recovery in this example?

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110




```
begin     // T1
write(A, 100)
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commit    // A=100; B=50
flush()

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write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

on a crash, all values in the cache go away
(because they're in memory, and memory is volatile)

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read(var):
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    cache[var] = cell_read(var)
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write(var, value):
  log.append(current_tid, update, var,
             read(var), value)
  cache[var] = value

flush(): // called "occasionally"
  cell_write(var, cache[var]) for each var
```

question: what needs to be repaired during recovery in this example?

both values in cell storage; we should have `A=80` and `B=70`

(the last committed values for both variables)

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110


```
begin     // T1
write(A, 100)
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  cache[var] = value

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recover(log):
  commits = []
  for record r in log[len(log)-1] .. log[0]:
    if r.type == COMMIT:
      commits.add(r.tid)
    if r.type == UPDATE and r.tid not in commits:
      cell_write(r.var, r.old_val) // undo
```

this is the previous `recover()` code; let’s see if it works

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
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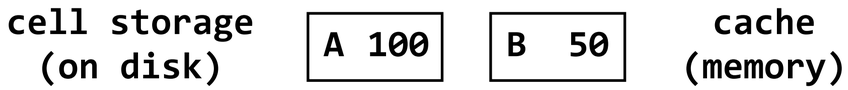


```
begin     // T1
write(A, 100)
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crash! 💥
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commits = []
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TID	T1	T1	T1	T2	T2	T2	T3
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TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
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TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
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begin     // T1
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commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

all other updates were committed; **B**'s value won't ever be changed

```
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  if var in cache:
    return cache[var]
  else:
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    cache[var] = cell_read(var)
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    if r.type == UPDATE and r.tid not in commits:
      cell_write(r.var, r.old_val) // undo
  for record r in log[0] .. log[len(log)-1]:
    if r.type == UPDATE and r.tid in commits:
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```

TID	T1	T1	T1	T2	T2	T2	T3
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write(B, read(B)+20)
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begin     // T3
write(A, read(A)+30)
crash! 💥
```

problem: recovery is still slow

```
read(var):
  if var in cache:
    return cache[var]
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    // may evict others from cache to cell storage
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      commits.add(r.tid)
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      cell_write(r.var, r.old_val) // undo
  for record r in log[0] .. log[len(log)-1]:
    if r.type == UPDATE and r.tid in commits:
      cell_write(r.var, r.new_value) // redo
```

TID	T1	T1	T1	T2	T2	T2	T3
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write(B, read(B)+20)
commit    // A=80; B=70

begin     // T3
write(A, read(A)+30)
crash! 💥
```

solution: write checkpoints and truncate the log

```
read(var):
  if var in cache:
    return cache[var]
  else:
    // may evict others from cache to cell storage
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  commits = []
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    if r.type == COMMIT:
      commits.add(r.tid)
    if r.type == UPDATE and r.tid not in commits:
      cell_write(r.var, r.old_val) // undo
  for record r in log[0] .. log[len(log)-1]:
    if r.type == UPDATE and r.tid in commits:
      cell_write(r.var, r.new_value) // redo
```

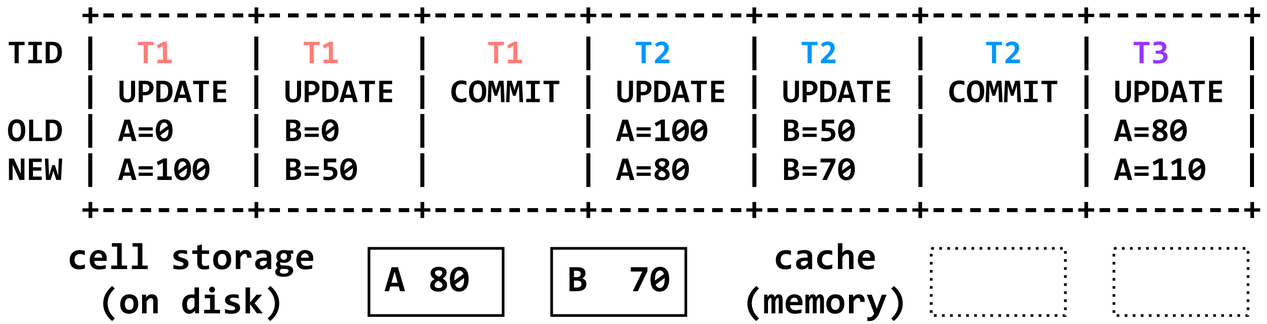

cell storage and the cache make reads and writes faster, but make our recovery process more complex. in particular, because cell storage is permanent, recovery must make sure it is correct — **undo**-ing any un-committed updates and **redo**-ing any updates that didn't get flushed from the cache

```
read(var):
  if var in cache:
    return cache[var]
  else:
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    cache[var] = cell_read(var)
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      commits.add(r.tid)
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      cell_write(r.var, r.old_val) // undo
  for record r in log[0] .. log[len(log)-1]:
    if r.type == UPDATE and r.tid in commits:
      cell_write(r.var, r.new_value) // redo
```
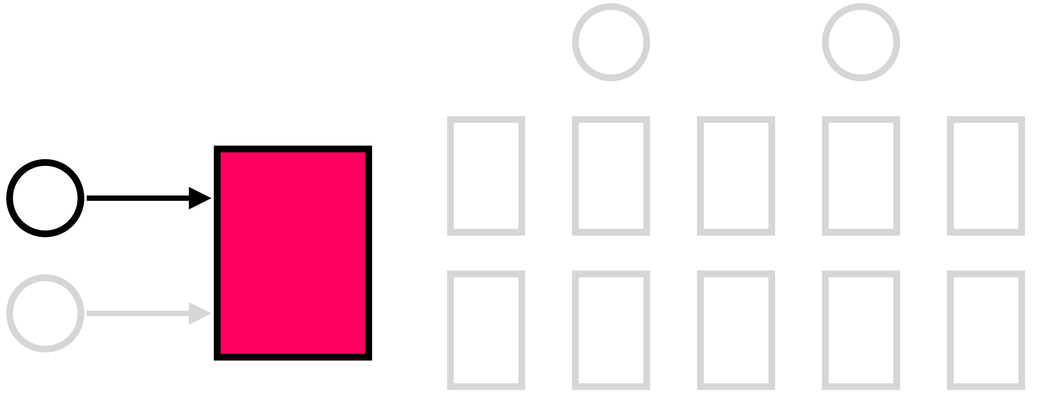

our goal is to build **reliable systems from unreliable components**. we want to build systems that serve many clients, store a lot of data, perform well, all while keeping availability high



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)

(write-ahead) logs provide **atomicity** with better performance than shadow copies. the primary benefit is making small appends for each update, rather than copy an entire file over for every change.

cell storage is used with the log to improve read performance, and **caches** and **truncation** can be used to improve write and recovery performance

the addition of these performance-improving techniques makes the system's **recovery** process more complex