6.033 Spring 2019

Lecture #16

- **Atomicity via Write-ahead logging**

goal: build reliable systems from unreliable components

the abstraction that makes that easier is

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

atomicity ⟶ **shadow copies** (simple, poor performance)

isolation ⟶ **?**

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

goal: build reliable systems from unreliable components

the abstraction that makes that easier is

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

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

isolation ⟶ **?**

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

```
transfer(bankfile, account_a, account_b, amount):
  bank = read_accounts(bankfile)
  bank[account_a] = bank[account_a] - amount
  bank[account_b] = bank[account_b] + amount
  write_accounts(tmp_bankfile)
  rename(tmp_bankfile, bankfile)
```

using shadow copies to abort on error

```
transfer(bankfile, account_a, account_b, amount):
  bank = read_accounts(bankfile)
  bank[account_a] = bank[account_a] - amount
  bank[account_b] = bank[account_b] + amount
  if bank[account_a] < 0:
    print "Not enough funds"
  else:
    write_accounts("tmp_bankfile")
    rename(tmp_bankfile, bankfile)
```

with transaction syntax

```
transfer(account_a, account_b, amount):
  begin
  write(account_a, read(account_a) - amount)
  write(account_b, read(account_b) + amount)
  if read(account_a) < 0: // not enough funds
    abort
else:
  commit
```

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

begin     // T2
A = A-20
B = B+20
commit    // A=80; B=70

begin     // T3
A = A+30
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
A = 100
B = 50
commit   // A=100; B=50

begin    // T2
A = A-20
B = B+20
commit   // A=80; B=70

begin    // T3
A = A+30
```

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

```
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
  if r.type == update and
     r.tid in commits and
     r.var == var:
      return r.new_value
```

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

```
begin    // T2
A = A-20
```

```
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
  if r.type == update and
     r.tid in commits and
     r.var == var:
      return r.new_value
```

```
commits = {}
```

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

```
begin    // T2
A = A-20
```

```
read(log, var):
  commits = {}
  // scan backwards
  for record r in log[len(log) - 1] .. log[0]:
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  if r.type == update and
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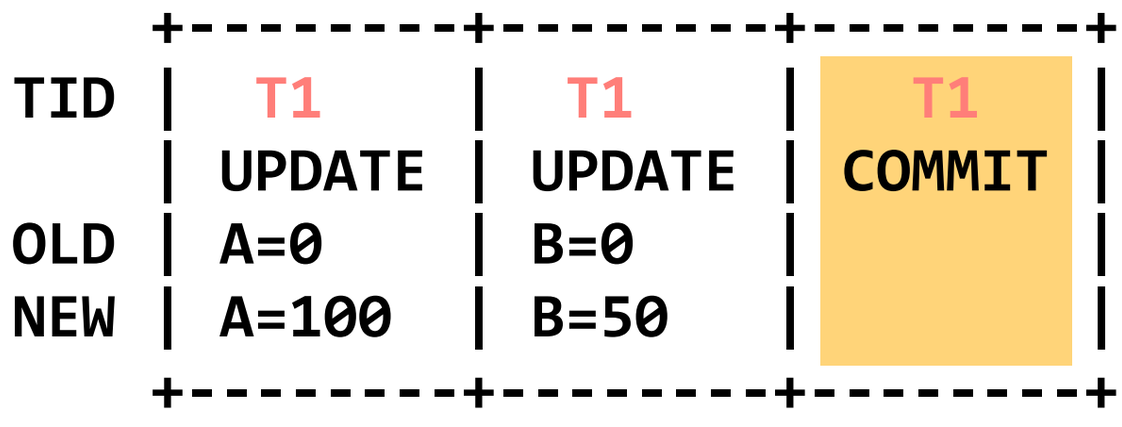
```

```
commits = {}
```




```
begin    // T2
A = A-20
```

```
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  commits = {}
  // scan backwards
  for record r in log[len(log) - 1] .. log[0]:
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  // find var's last committed value
  if r.type == update and
     r.tid in commits and
     r.var == var:
      return r.new_value
```

```
commits = {T1}
```

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

```
begin     // T2
A = A-20
```

```
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
  if r.type == update and
     r.tid in commits and
     r.var == var:
      return r.new_value
```

```
commits = {T1}
```

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

```
begin     // T2
A = A-20
```

```
read(log, var):
  commits = {}
  // scan backwards
  for record r in log[len(log) - 1] .. log[0]:
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  if r.type == update and
     r.tid in commits and
     r.var == var:
      return r.new_value
```

```
commits = {T1}
```

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

```
begin     // T2
A = A-20
```

```
read(log, var):
  commits = {}
  // scan backwards
  for record r in log[len(log) - 1] .. log[0]:
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  if r.type == commit:
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  // find var's last committed value
  if r.type == update and
     r.tid in commits and
     r.var == var:
      return r.new_value
```

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

```
begin     // T2
A = A-20
A = A-30
```

```
read(log, var):
  commits = {}
  // scan backwards
  for record r in log[len(log) - 1] .. log[0]:
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     r.tid in commits and
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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

```
begin     // T2
A = A-20
A = A-30
```

```
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
  if r.type == update and
     (r.tid in commits or r.tid == current_tid) and
     r.var == var:
      return r.new_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
A = 100
B = 50
commit

begin     // T2
A = A-20
B = B+20
commit

begin     // T3
A = A+30
crash! 💥
```

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

performance?

problem: reads are 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

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
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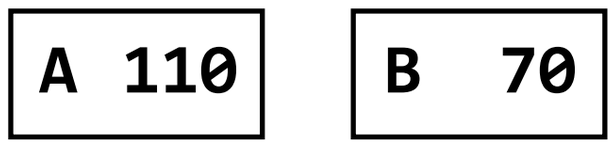
cell storage (on disk)




```
recover(log):
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  for record r in log[len(log)-1] .. log[0]:
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OLD	A=0	B=0		A=100	B=50		A=80
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cell storage (on disk)

A	110

B	70

commits = {}

```
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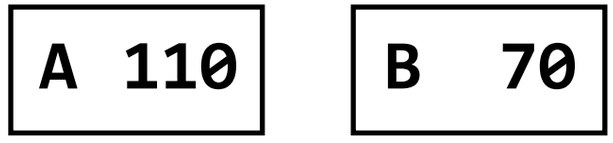
cell storage (on disk)



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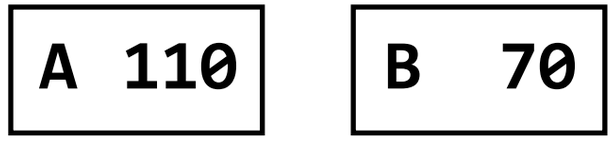

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A	110

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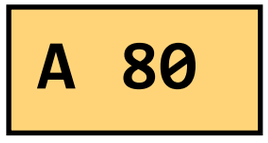

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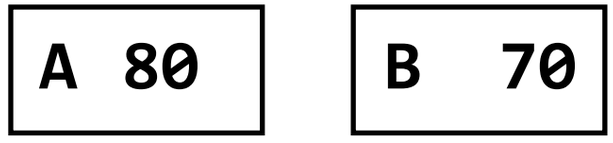
cell storage (on disk)



commits = {}

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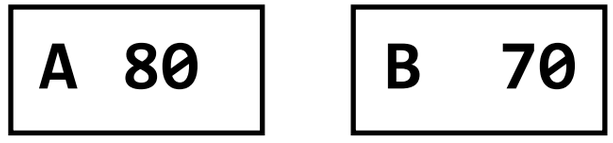
cell storage (on disk)



commits = {}

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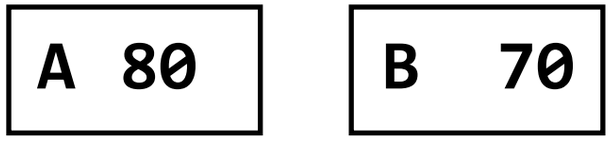
TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

cell storage (on disk)



commits = {}

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  commits = {}
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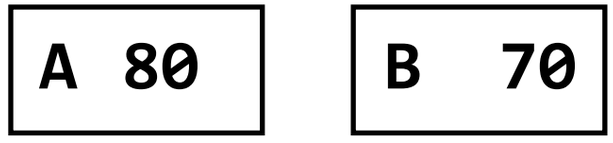
cell storage (on disk)



commits = {T2}

```
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
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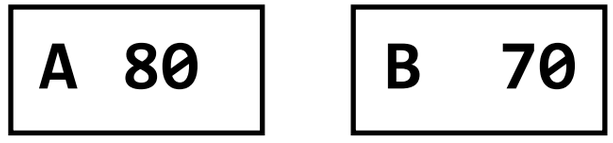
cell storage (on disk)



commits = {T2}

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  for record r in log[len(log)-1] .. log[0]:
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      commits.add(r.tid)
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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

cell storage (on disk)

A 80

B 70

commits = {T2}

```
recover(log):
  commits = {}
  for record r in log[len(log)-1] .. log[0]:
    if r.type == commit:
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OLD	A=0	B=0		A=100	B=50		A=80
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cell storage (on disk)

A	80

B	70

commits = {T2}

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recover(log):
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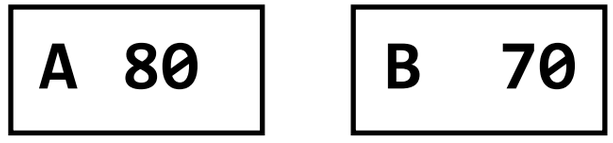
cell storage (on disk)



commits = {T2}

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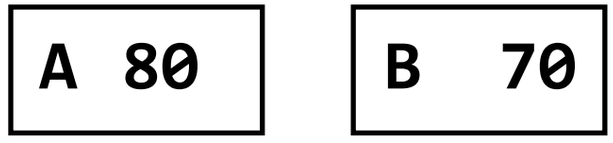
cell storage (on disk)



commits = {T2}

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cell storage (on disk)

A	80

B	70

commits = {T2}

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recover(log):
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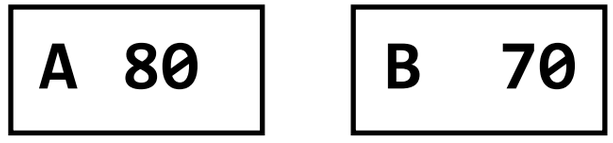
NEW	A=100	B=50		A=80	B=70		A=110

cell storage (on disk)

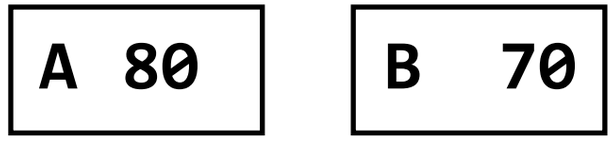


commits = {T2}

```
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)



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	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
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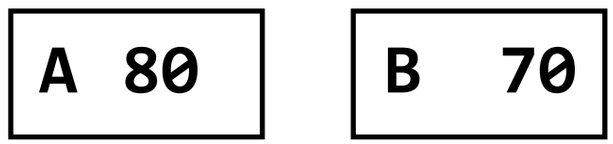
cell storage (on disk)



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recover(log):
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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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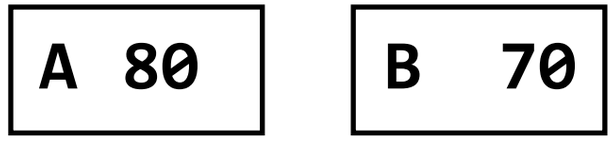
cell storage (on disk)



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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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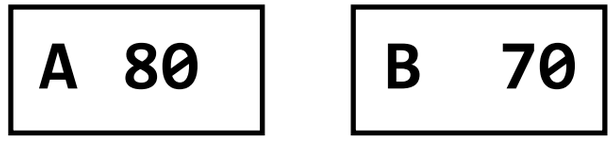
cell storage (on disk)



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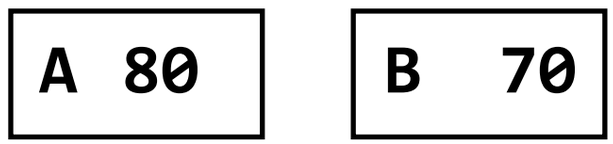
cell storage (on disk)



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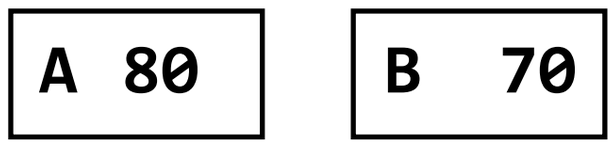
NEW	A=100	B=50		A=80	B=70		A=110

cell storage (on disk)



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	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
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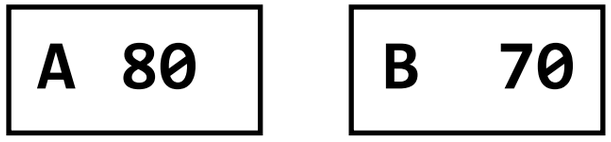
cell storage (on disk)



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  for record r in log[len(log)-1] .. log[0]:
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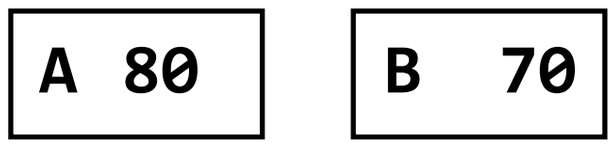

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	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
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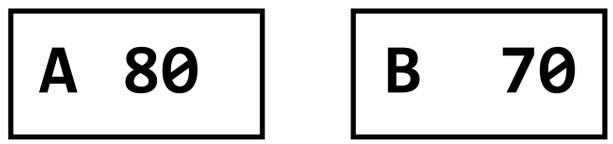
cell storage (on disk)



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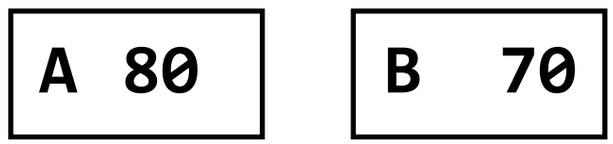
cell storage (on disk)



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	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
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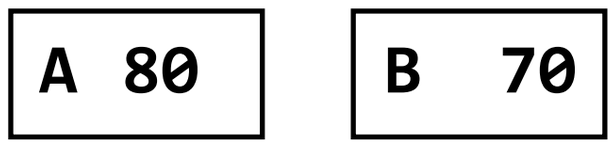
cell storage (on disk)



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	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
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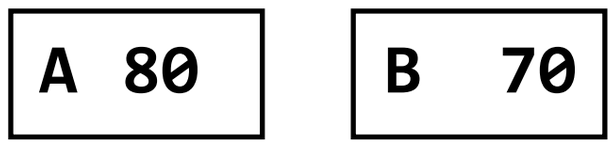
cell storage (on disk)



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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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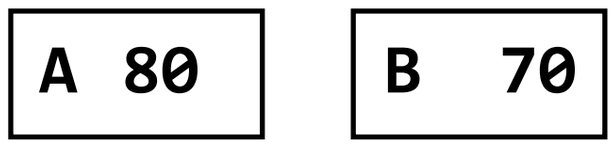
cell storage (on disk)



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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

cell storage (on disk)

A 80

B 70

commits = {T2, T1}

```
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:
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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

cell storage (on disk)

A	80

B	70

commits = {T2, T1}

```
recover(log):
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  for record r in log[len(log)-1] .. log[0]:
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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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cell storage (on disk)

A	80

B	70

commits = {T2, T1}

```
recover(log):
  commits = {}
  for record r in log[len(log)-1] .. log[0]:
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cell storage (on disk)

A 80

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commits = {T2, T1}

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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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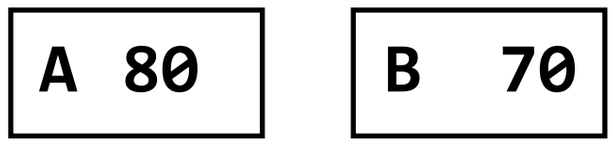
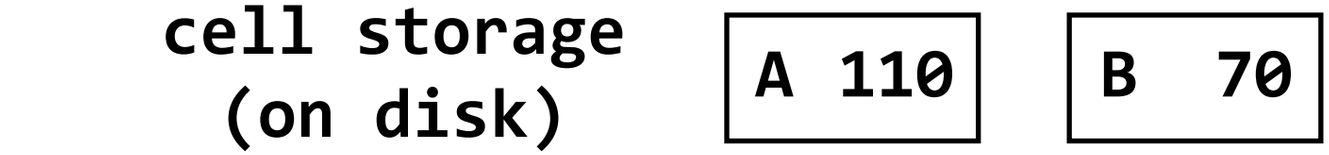
cell storage (on disk)




```
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



performance?

problem: read performance is now great, but writes got (a little bit) slower and recovery got (a lot) slower

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


```
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
OLD	A=0	B=0		A=100	B=50		A=80
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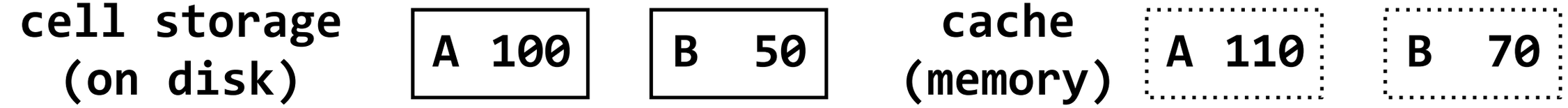

suppose we flushed the cache after T1 committed,
but have not flushed it since then

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


```
recover(log):
  commits = {}
  for record r in log[len(log)-1] .. log[0]:
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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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	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
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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
```

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

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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recover(log):
  commits = {}
for record r in log[len(log)-1] .. log[0]:
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  if r.type == update and r.tid not in commits:
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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
	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
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

performance?

problem: recovery is still 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

performance?

solution: write checkpoints and truncate the log

- **(Write-ahead) logs** provide **atomicity** with better performance than shadow copies. The primary benefit is making small appends for each update, rather than copying and 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.