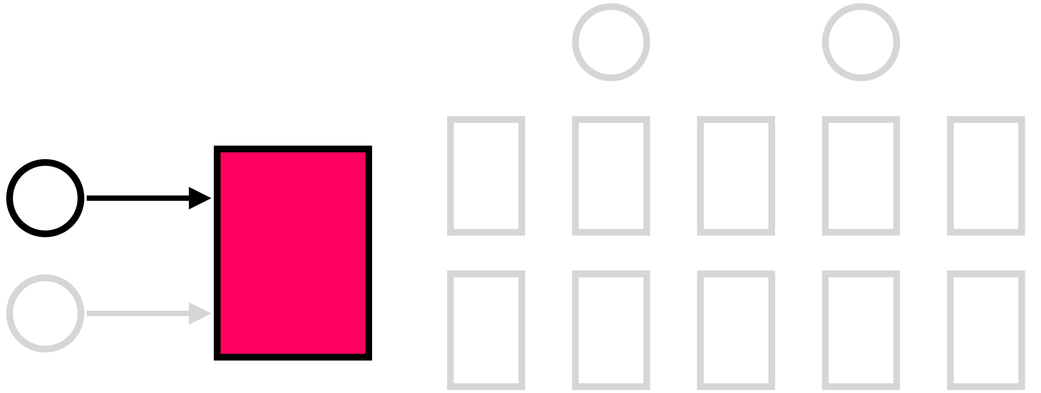
6.033 Spring 2021

Lecture #16: Atomicity via Logging

superior to shadow copies in almost every way

Katrina LaCurts | lacurts@mit.edu | 6.033 2021

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



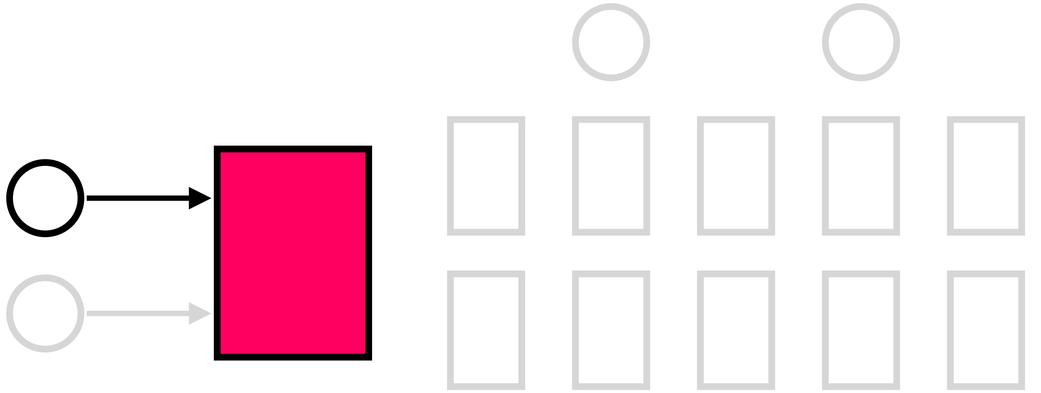
transactions — which provide **atomicity** and **isolation** — make it easier for us to reason about failures

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: we have this working for one user and one file via *shadow copies*, but they perform poorly

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

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



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: 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)

```
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: 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
	UPDATE	UPDATE	COMMIT
OLD	A=0	B=0	
NEW	A=100	B=50	

```
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)
```

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 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     // 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)
```

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

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  // scan backwards
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    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
```

```
commits = [T1]
```

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

```
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)
```

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

begin     // T2
write(A, read(A)-20)
write(A, read(A)-30)
commit    // A=50; B=50

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

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

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
```

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 UPDATE	T1 UPDATE	T1 COMMIT	T2 UPDATE	T2 UPDATE	T2 COMMIT	T3 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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begin     // T3
write(A, read(A)+30)
crash! 💥
```

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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 or r.tid == current_tid)
      and r.var == var:
        return r.new_value
```

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
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```
begin     // T1
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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)
```

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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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
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      cell_write(r.var, r.old_val) // undo


commits = []
```
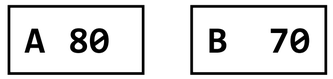

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

cell storage (on disk)

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```
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write(var, value):
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  cell_write(var, value)


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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
```

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

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


```
begin     // T1
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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
```

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
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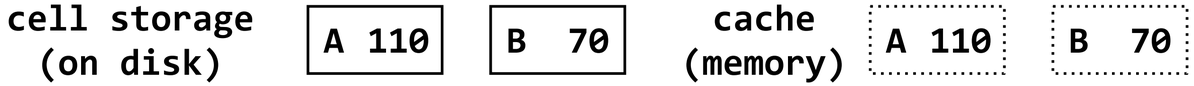


```
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commit    // A=100; B=50

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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)
```

```
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

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

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

```
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,
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  cache[var] = value

flush(): // called "occasionally"
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TID	T1	T1	T1	T2	T2	T2	T3
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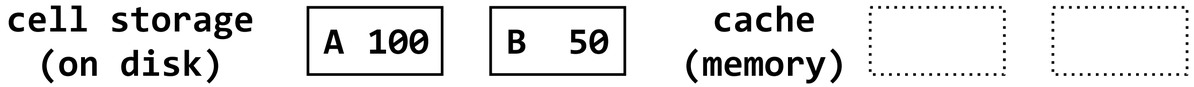


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begin     // T3
write(A, read(A)+30)
crash! 💥
```

```
read(var):
  if var in cache:
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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

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
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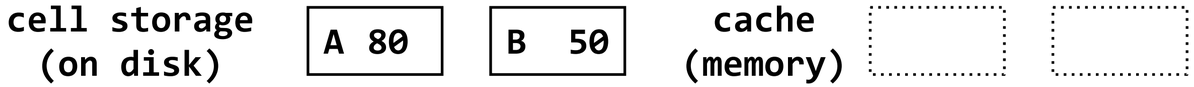


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read(var):
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write(var, value):
  log.append(current_tid, update, var,
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  cache[var] = value

flush(): // called "occasionally"
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      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
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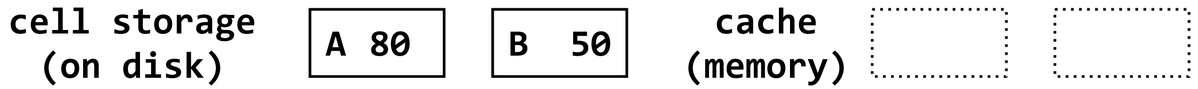


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begin     // T1
write(A, 100)
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write(A, read(A)-20)
write(B, read(B)+20)
commit    // A=80; B=70

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

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

```
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]

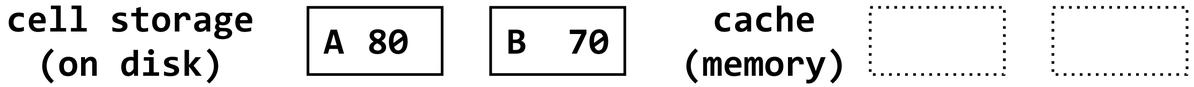
write(var, value):
  log.append(current_tid, update, var,
             read(var), value)
  cache[var] = value

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

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

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begin     // T1
write(A, 100)
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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: recovery is still slow

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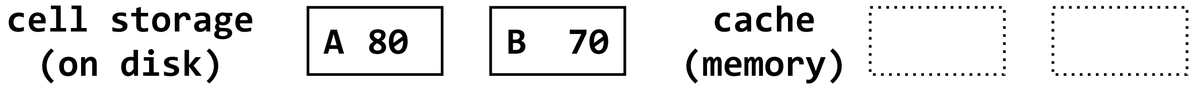

TID	T1	T1	T1	T2	T2	T2	T3
	UPDATE	UPDATE	COMMIT	UPDATE	UPDATE	COMMIT	UPDATE
OLD	A=0	B=0		A=100	B=50		A=80
NEW	A=100	B=50		A=80	B=70		A=110

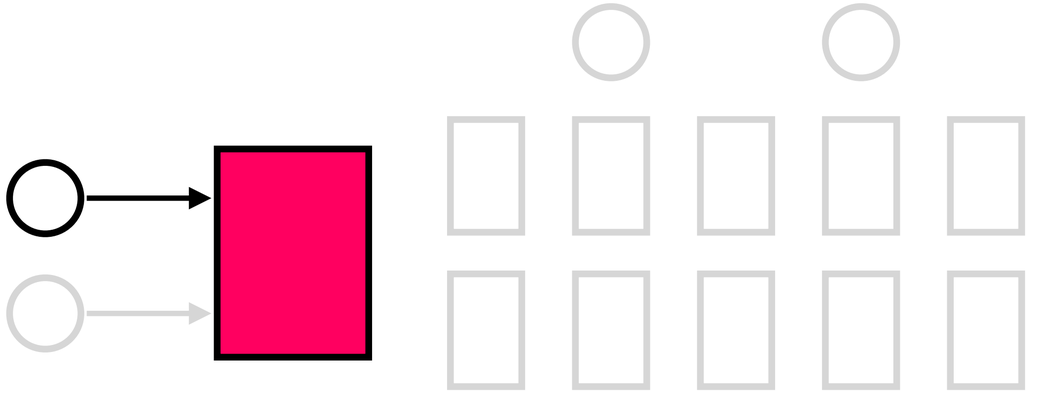



```
begin     // T1
write(A, 100)
write(B, 50)
commit    // A=100; B=50

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! 💥
```

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
    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


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
  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