IF YOU WANT TO USE A LAPTOP, SIT ON THE LEFT SIDE OF THE CLASSROOM
• When replication fails us
  • Atomicity via shadow copies
  • Isolation
  • Transactions
high-level goal: build reliable systems from unreliable components
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this is difficult because reasoning about failures is difficult. we need some abstractions that will let us simplify.
atomicity

an action is atomic if it **happens completely or not at all**. if we can guarantee atomicity, it will be much easier to reason about failures
transfer (bank, account_a, account_b, amount):
    bank[account_a] = bank[account_a] - amount
    bank[account_b] = bank[account_b] + amount
transfer (bank, account_a, account_b, amount):
    bank[account_a] = bank[account_a] - amount
    bank[account_b] = bank[account_b] + amount

← crash!💥
transfer (bank, account_a, account_b, amount):
    bank[account_a] = bank[account_a] - amount
    bank[account_b] = bank[account_b] + amount

problem: account_a lost amount dollars, but account_b didn’t gain amount dollars
transfer (bank, account_a, account_b, amount):
    bank[account_a] = bank[account_a] - amount
    bank[account_b] = bank[account_b] + amount

solution: make this action atomic. ensure that the system completes both steps or neither step.
quest for atomicity: attempt 1

transfer (bank_file, account_a, account_b, amount):

  bank = read_accounts(bank_file)
  bank[account_a] = bank[account_a] - amount
  bank[account_b] = bank[account_b] + amount
  write_accounts(bank_file)
quest for atomicity: attempt 1

transfer (bank_file, account_a, account_b, amount):

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write_accounts(bank_file)

-crash!
quest for atomicity: attempt 1

transfer (bank_file, account_a, account_b, amount):

```python
bank = read_accounts(bank_file)
bank[account_a] = bank[account_a] - amount
bank[account_b] = bank[account_b] + amount
write_accounts(bank_file) ← crash!💥
```
quest for atomicity: attempt 1

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```python
bank = read_accounts(bank_file)
bank[account_a] = bank[account_a] - amount
bank[account_b] = bank[account_b] + amount
write_accounts(bank_file) ← crash!💥
```

problem: a crash during write_accounts leaves bank_file in an intermediate state
quest for atomicity: attempt 2
(shadow copies)

transfer (bank_file, account_a, account_b, amount):
    bank = read_accounts(bank_file)
    bank[account_a] = bank[account_a] - amount
    bank[account_b] = bank[account_b] + amount
    write_accounts(tmp_file)
    rename(tmp_file, bank_file)
**quest for atomicity: attempt 2**

(shadow copies)

\[
\text{transfer (bank_file, account_a, account_b, amount):}
\]

\[
\begin{align*}
\text{bank} & = \text{read_accounts(bank_file)} \\
\text{bank}[\text{account_a}] & = \text{bank}[\text{account_a}] - \text{amount} \\
\text{bank}[\text{account_b}] & = \text{bank}[\text{account_b}] + \text{amount}
\end{align*}
\]

\[
\text{write_accounts(tmp_file)}
\]

\[
\text{rename(tmp_file, bank_file)}
\]

\[\text{crash! ⚡}\]
quest for atomicity: attempt 2
(shadow copies)

transfer (bank_file, account_a, account_b, amount):
    bank = read_accounts(bank_file)
    bank[account_a] = bank[account_a] - amount
    bank[account_b] = bank[account_b] + amount
    write_accounts(tmp_file)
    rename(tmp_file, bank_file)

    crash!💥
quest for atomicity: attempt 2
(shadow copies)

```python
transfer (bank_file, account_a, account_b, amount):
    bank = read_accounts(bank_file)
    bank[account_a] = bank[account_a] - amount
    bank[account_b] = bank[account_b] + amount
    write_accounts(tmp_file)
    rename(tmp_file, bank_file)← crash!💥
```
quest for atomicity: attempt 2
(shadow copies)

transfer (bank_file, account_a, account_b, amount):
    bank = read_accounts(bank_file)
    bank[account_a] = bank[account_a] - amount
    bank[account_b] = bank[account_b] + amount
    write_accounts(tmp_file)
    rename(tmp_file, bank_file)← crash!💥

problem: a crash during rename potentially leaves bank_file in an intermediate state
quest for atomicity: attempt 2
(shadow copies)

transfer (bank_file, account_a, account_b, amount):
   bank = read_accounts(bank_file)
   bank[account_a] = bank[account_a] - amount
   bank[account_b] = bank[account_b] + amount
   write_accounts(tmp_file)
   rename(tmp_file, bank_file)
   crash!

solution: make rename atomic
quest for atomicity: making rename atomic
quest for atomicity: making rename atomic

directory entries
filename “bank_file” -> inode 1
filename “tmp_file” -> inode 2
quest for atomicity: making rename atomic

directory entries
  filename “bank_file” -> inode 1
  filename “tmp_file” -> inode 2

inode 1: // old data
  data blocks: [..]
  refcount: 1

inode 2: // new data
  data blocks: [..]
  refcount: 1
quest for atomicity: making rename atomic

directory entries
  filename “bank_file” -> inode 1
  filename “tmp_file” -> inode 2

inode 1: // old data
  data blocks: [..]
  refcount: 1

inode 2: // new data
  data blocks: [..]
  refcount: 1

rename(tmp_file, orig_file):
  // point bank_file’s dirent at inode 2
  // delete tmp_file’s dirent
  // remove refcount on inode 1
quest for atomicity: making rename atomic

directory entries
filename "bank_file" -> inode 1
filename "tmp_file" -> inode 2

inode 1: // old data
  data blocks: [...]
  refcount: 1

inode 2: // new data
  data blocks: [...]
  refcount: 1

rename(tmp_file, orig_file):
  tmp_inode = lookup(tmp_file) // = 2
  orig_inode = lookup(orig_file) // = 1

  // point bank_file’s dirent at inode 2
  // delete tmp_file’s dirent
  // remove refcount on inode 1
quest for atomicity: making rename atomic

directory entries
   filename “bank_file” -> inode 2
   filename “tmp_file” -> inode 2

inode 1: // old data
   data blocks: [..]
   refcount: 1

inode 2: // new data
   data blocks: [..]
   refcount: 1

rename(tmp_file, orig_file):
   tmp_inode = lookup(tmp_file)  // = 2
   orig_inode = lookup(orig_file)  // = 1

orig_file dirent = tmp_inode
   // delete tmp_file’s dirent
   // remove refcount on inode 1
quest for atomicity: making rename atomic

directory entries
filename “bank_file” -> inode 2

inode 1: // old data
  data blocks: [..]
  refcount: 1

inode 2: // new data
  data blocks: [..]
  refcount: 1

rename(tmp_file, orig_file):
  tmp_inode = lookup(tmp_file) // = 2
  orig_inode = lookup(orig_file) // = 1

orig_file dirent = tmp_inode
remove tmp_file dirent
// remove refcount on inode 1
directory entries
filename “bank_file” -> inode 2

inode 1: // old data
  data blocks: [...]  
  refcount: 0

inode 2: // new data
  data blocks: [...]  
  refcount: 1

rename(tmp_file, orig_file):
  tmp_inode = lookup(tmp_file)   // = 2
  orig_inode = lookup(orig_file)   // = 1

orig_file dirent = tmp_inode
remove tmp_file dirent
decref(orig_inode)
quest for atomicity: making rename atomic

directory entries
  filename “bank_file” -> inode 1
  filename “tmp_file” -> inode 2

inode 1: // old data
  data blocks: [..]
  refcount: 1

inode 2: // new data
  data blocks: [..]
  refcount: 1

rename(tmp_file, orig_file):
  tmp_inode = lookup(tmp_file) // = 2
  orig_inode = lookup(orig_file) // = 1

  orig_file dirent = tmp_inode
  remove tmp_file dirent
  decref(orig_inode)

  crash! 💥
directory entries

filename "bank_file" -> inode 1
filename "tmp_file" -> inode 2

inode 1: // old data
   data blocks: [..]
   refcount: 1

inode 2: // new data
   data blocks: [..]
   refcount: 1

rename(tmp_file, orig_file):
   tmp_inode = lookup(tmp_file)  // = 2
   orig_inode = lookup(orig_file) // = 1

   orig_file dirent = tmp_inode
   remove tmp_file dirent
   decref(orig_inode)

quest for atomicity: making rename atomic

rename didn’t happen

crash! 💥
rename(tmp_file, orig_file):

tmp_inode = lookup(tmp_file)  // = 2
orig_inode = lookup(orig_file)  // = 1

orig_file dirent = tmp_inode
remove tmp_file dirent

decref(orig_inode)

crash!💥
directory entries
    filename "bank_file" -> inode 2
    filename "tmp_file" -> inode 2

inode 1: // old data
    data blocks: [...]  
    refcount: 1

inode 2: // new data
    data blocks: [...]  
    refcount: 1

rename(tmp_file, orig_file):
    tmp_inode = lookup(tmp_file) // = 2
    orig_inode = lookup(orig_file) // = 1

orig_file dirent = tmp_inode  
remove tmp_file dirent

decref(orig_inode)

quest for atomicity: making rename atomic

rename happened, but refcounts are wrong

crash! 💥
directory entries
    filename “bank_file” -> inode ?
    filename “tmp_file” -> inode 2

inode 1: // old data
    data blocks: [..]
    refcount: 1

inode 2: // new data
    data blocks: [..]
    refcount: 1

rename(tmp_file, orig_file):
    tmp_inode = lookup(tmp_file)  // = 2
    orig_inode = lookup(orig_file)  // = 1

orig_file dirent = tmp_inode ← crash!💥
remove tmp_file dirent
decref(orig_inode)
quest for atomicity: making rename atomic

directory entries
filename “bank_file” -> inode ?
filename “tmp_file” -> inode 2

inode 1: // old data
  data blocks: […]
  refcount: 1

inode 2: // new data
  data blocks: […]
  refcount: 1

rename(tmp_file, orig_file):
  tmp_inode = lookup(tmp_file) // = 2
  orig_inode = lookup(orig_file) // = 1

orig_file dirent = tmp_inode ← crash! 💥
remove tmp_file dirent
decref(orig_inode)

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quest for atomicity: making rename atomic

directory entries
  filename “bank_file” -> inode ?
  filename “tmp_file” -> inode 2

inode 1: // old data
  data blocks: [...]  
  refcount: 1

inode 2: // new data
  data blocks: [...]  
  refcount: 1

rename(tmp_file, orig_file):
  tmp_inode = lookup(tmp_file)  // = 2
  orig_inode = lookup(orig_file)  // = 1

orig_file dirent = tmp_inode ← crash!💥
remove tmp_file dirent  
decref(orig_inode)      crash during this line seems bad..
but is okay because single-sector writes are themselves atomic
we’re trying to make a sequence of actions atomic using shadow copies: write to a temporary file, and then rename it to the original.

rename itself must be atomic, and we’ve almost got that working — thanks in part to atomic single-sector writes — but our refcounts aren’t quite correct.
**quest for atomicity:** making rename atomic

directory entries
- filename “bank_file” -> inode 2
- filename “tmp_file” -> inode 2

inode 1: // old data
- data blocks: [..]
- refcount: 1

inode 2: // new data
- data blocks: [..]
- refcount: 1

rename(tmp_file, orig_file):
- tmp_inode = lookup(tmp_file) // = 2
- orig_inode = lookup(orig_file) // = 1

orig_file dirent = tmp_inode
remove tmp_file dirent
decref(orig_inode)

**crash!**

rename happened, but refcounts are wrong
quest for atomicity: making rename atomic

directory entries
  filename “bank_file” -> inode 2
  filename “tmp_file” -> inode 2

inode 1: // old data
  data blocks: [..]
  refcount: 1

inode 2: // new data
  data blocks: [..]
  refcount: 1

rename(tmp_file, orig_file):
  tmp_inode = lookup(tmp_file)    // = 2
  orig_inode = lookup(orig_file)  // = 1
  incref(tmp_inode)
  orig_file dirent = tmp_inode
  decref(orig_inode)
  remove tmp_file dirent
  decref(tmp_inode)
quest for atomicity: making rename atomic

directory entries
  filename "bank_file" -> inode 2
  filename "tmp_file" -> inode 2

inode 1: // old data
  data blocks: [..]
  refcount: 1

inode 2: // new data
  data blocks: [..]
  refcount: 1

rename(tmp_file, orig_file):
  tmp_inode = lookup(tmp_file)  // = 2
  orig_inode = lookup(orig_file)  // = 1
  incref(tmp_inode)
  orig_file dirent = tmp_inode
  decref(orig_inode)
  remove tmp_file dirent
  decref(tmp_inode)

problem: this is a mess, and is still incorrect
solution: recover from failure
(clean things up)

recover(disk):
    for inode in disk.inodes:
        inode.refcount = find_all_refs(disk.root_dir, inode)
    if exists("tmp_file"):
        unlink("tmp_file")
quest for atomicity: attempt 2
(shadow copies)

transfer (bank_file, account_a, account_b, amount):
  bank = read_accounts(bank_file)
  bank[account_a] = bank[account_a] - amount
  bank[account_b] = bank[account_b] + amount
  write_accounts(tmp_file)
  rename(tmp_file, bank_file)
atomicity
(first abstraction)
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not quite solved; shadow copies perform poorly even for a single user and a single file, and we haven’t even talked about concurrency
**atomicity**
(first abstraction)

not quite solved; shadow copies perform poorly even for a single user and a single file, and we haven’t even talked about concurrency

**isolation**
(second abstraction)

if we guarantee isolation, then two actions A1 and A2 will appear to have run **serially** even if they were executed concurrently (i.e., A1 before A2, or vice versa)
transactions: provide atomicity and isolation

Transaction 1
begin
  transfer(A, B, 20)
  withdraw(B, 10)
end

Transaction 2
begin
  transfer(B, C, 5)
  deposit(A, 5)
end
transactions: provide atomicity and isolation

Transaction 1
begin
transfer(A, B, 20)
withdraw(B, 10)
end

Transaction 2
begin
transfer(B, C, 5)
deposit(A, 5)
end

atomicity: each transaction will appear to have run to completion, or not at all
transactions: provide atomicity and isolation

Transaction 1
begin
transfer(A, B, 20)
withdraw(B, 10)
end

Transaction 2
begin
transfer(B, C, 5)
deposit(A, 5)
end

atomicity: each transaction will appear to have run to completion, or not at all

isolation: when multiple transactions are run concurrently, it will appear as if they were run sequentially (serially)
atomicity and isolation — and thus, transactions — make it easier to reason about failures (and concurrency)
transfer (bank_file, account_a, account_b, amount):

    acquire(lock)
    bank = read_accounts(bank_file)
    bank[account_a] = bank[account_a] - amount
    bank[account_b] = bank[account_b] + amount
    write_accounts("tmp_file")
    rename("tmp_file", bank_file)
    release(lock)
transfer (bank_file, account_a, account_b, amount):
acquire(lock)
bank = read_accounts(bank_file)
bank[account_a] = bank[account_a] - amount
bank[account_b] = bank[account_b] + amount
write_accounts("tmp_file")
rename("tmp_file", bank_file)
release(lock)

couldn’t we just put locks around everything?
(isn’t that what locks are for?)
transer (bank_file, account_a, account_b, amount):
    acquire(lock)
    bank = read_accounts(bank_file)
    bank[account_a] = bank[account_a] - amount
    bank[account_b] = bank[account_b] + amount
    write_accounts("tmp_file")
    rename("tmp_file", bank_file)
    release(lock)

this particular strategy will perform poorly
    (would force a single transfer at a time)
transfer (bank_file, account_a, account_b, amount):
    acquire(lock)
    bank = read_accounts(bank_file)
    bank[account_a] = bank[account_a] - amount
    bank[account_b] = bank[account_b] + amount
    write_accounts("tmp_file")
    rename("tmp_file", bank_file)
    release(lock)

this particular strategy will perform poorly
    (would force a single transfer at a time)

locks sometimes require global reasoning,
    which is messy
eventually, we’ll incorporate locks, but in a systematic way
goal: to implement transactions, which provide atomicity and isolation, while not hindering performance
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atomicity ≠ shadow copies. work, but perform poorly and don’t allow for concurrency
**goal:** to implement **transactions**, which provide atomicity and isolation, while not hindering performance.

**atomicity** → **shadow copies.** work, but perform poorly and don’t allow for concurrency

**isolation** → ?

(coarse-grained locks perform poorly, finer-grained locks are difficult to reason about)
**goal:** to implement **transactions**, which provide atomicity and isolation, while not hindering performance.

**atomicity** → **shadow copies.** work, but perform poorly and don’t allow for concurrency.

**isolation** → (coarse-grained locks perform poorly, finer-grained locks are difficult to reason about).

Eventually, we also want transaction-based systems to be **distributed:** to run across multiple machines.
• **Transactions** provide **atomicity** and **isolation**, both of which make it easier for us to reason about failures because we don’t have to deal with intermediate states.

• **Shadow copies** are one way to achieve atomicity. The work, but perform poorly: require copying an entire file even for small changes, and don’t allow for concurrency.