• 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

```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(bank_file)
```
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
    crash!💥
write_accounts(bank_file)
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

transfer (bank_file, account_a, account_b, amount):

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

problem: a crash during write_accounts leaves \text{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)

```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)

```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)  # crash!
    rename(tmp_file, bank_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)  

\[\text{crash!} \]
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!💥

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
• When replication fails us
  • Atomicity via shadow copies
  • Isolation
  • Transactions
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
quest for atomicity: making rename atomic

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! 💥
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!💥
rename didn’t happen
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)

quest for atomicity: making rename atomic
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
decrref(orig_inode)

 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

orig_file dirent = tmp_inode
remove tmp_file dirent
decrref(orig_inode)

 rename happened, but refcounts are wrong
**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
deeref(`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    crash during this line seems bad..
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)

crash during this line seems bad...
but is okay because single-sector writes
are themselves atomic
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`
- `inref(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)
• When replication fails us
  • Atomicity via shadow copies
  • Isolation
  • Transactions
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):

    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)
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?)
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)
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.