Distributed Systems

Catch-up Lecture:
Consistency Model Implementations

Slides redundant with Lec 11,12

Slide acks: Jinyang Li, Robert Morris, Dave Andersen

Outline

- Last times: Consistency models
  - Strict consistency
  - Sequential consistency
  - Causal consistency
  - Eventual consistency
- How do you define them?

- Today: Basic ideas for implementing them
  - Sequential consistency
  - Eventual consistency
  - // Causal consistency (Promiscuous covered that)

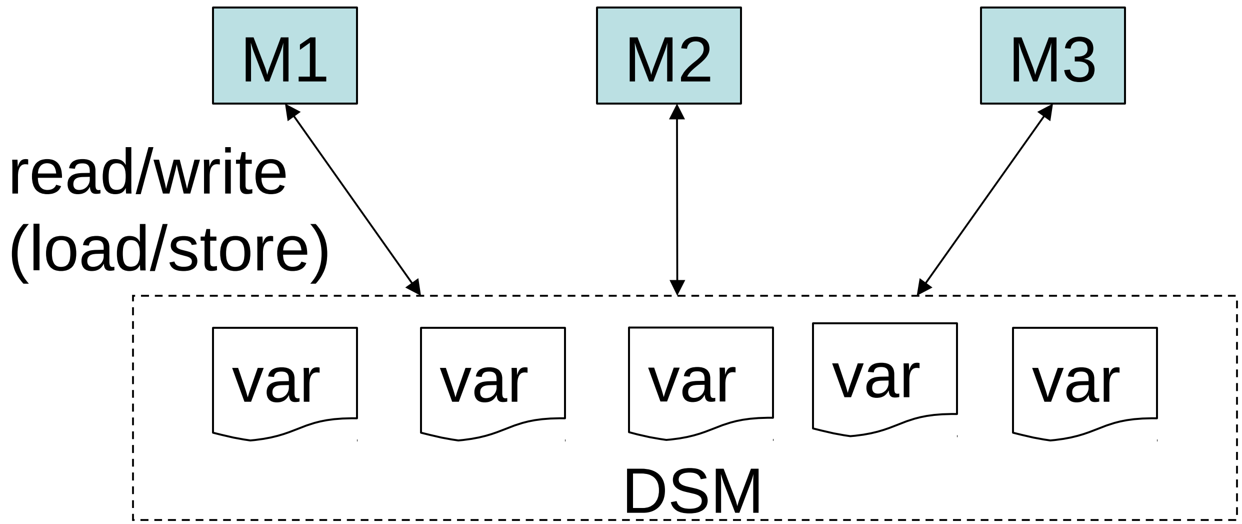
Outline

- How do you define these consistency models:
  - Sequential consistency
    - All memory/storage accesses appear executed in a single order by all processes
  - Eventual consistency
    1. All replicas *eventually* become identical and no writes are lost
    2. All replicas *eventually* apply all updates in a single order

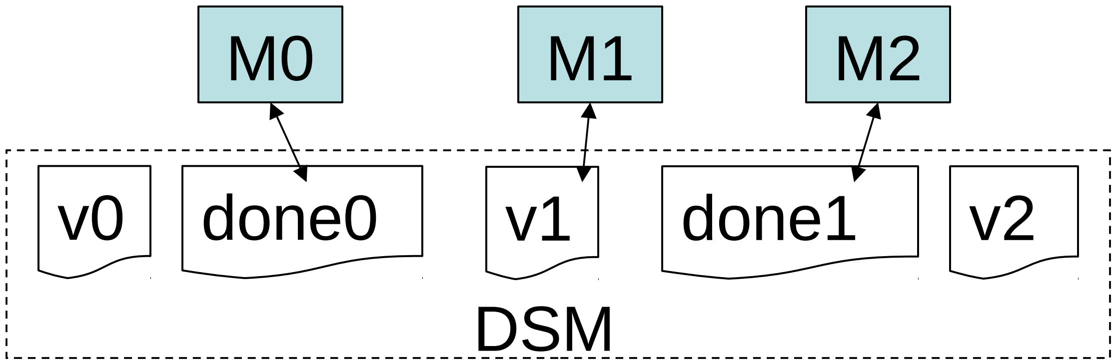
- Implementation summary:
  - Sequential consistency
    - Serialize all requests through a master, invalidate caches, wait for writes to complete → Ivy, a distributed shared mem system (DSM)
  - Eventual consistency
    - Perform reads/writes asynchronously, synch back with others later and solve conflicts at that time → file synchronizers

Distributed Shared Memory (DSM)

- Two models for communication in distributed systems:
  - message passing
  - shared memory
- Shared memory is often thought more intuitive to write parallel programs than message passing
  - Each machine can access a common address space



Example Application



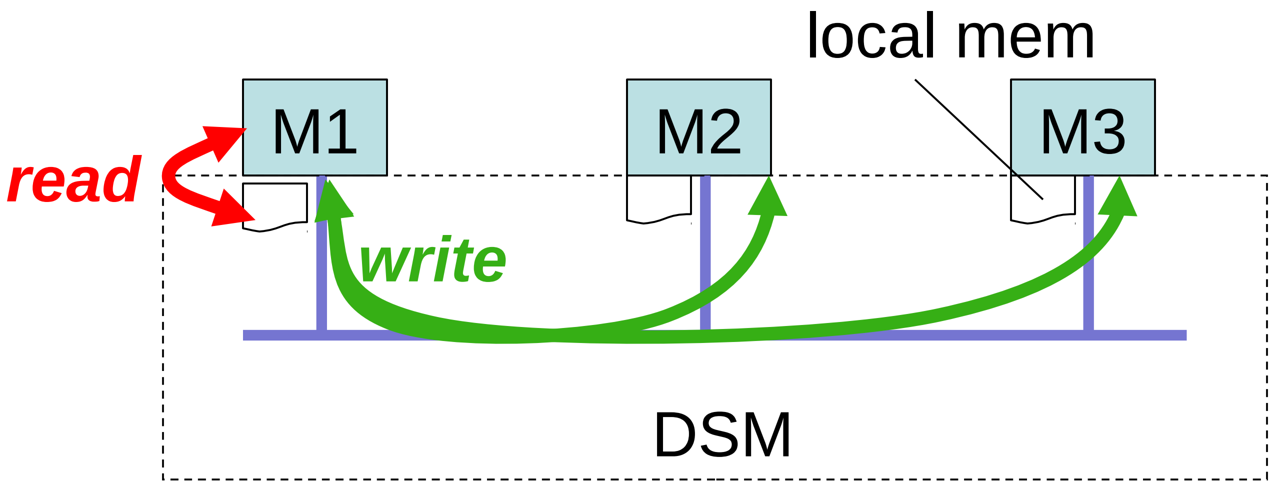
M0:
```
v0 = f0();
done0 = 1;
```

M1:
```
while (done0 == 0)
    ;
v1 = f1(v0);
done1 = 1;
```

M2:
```
while (done1 == 0)
    ;
v2 = f2(v0, v1);
```

- What’s the intuitive intent?
  - M2 should execute f2() with results from M0 and M1
  - waiting for M1 implies waiting for M0

Naïve DSM System

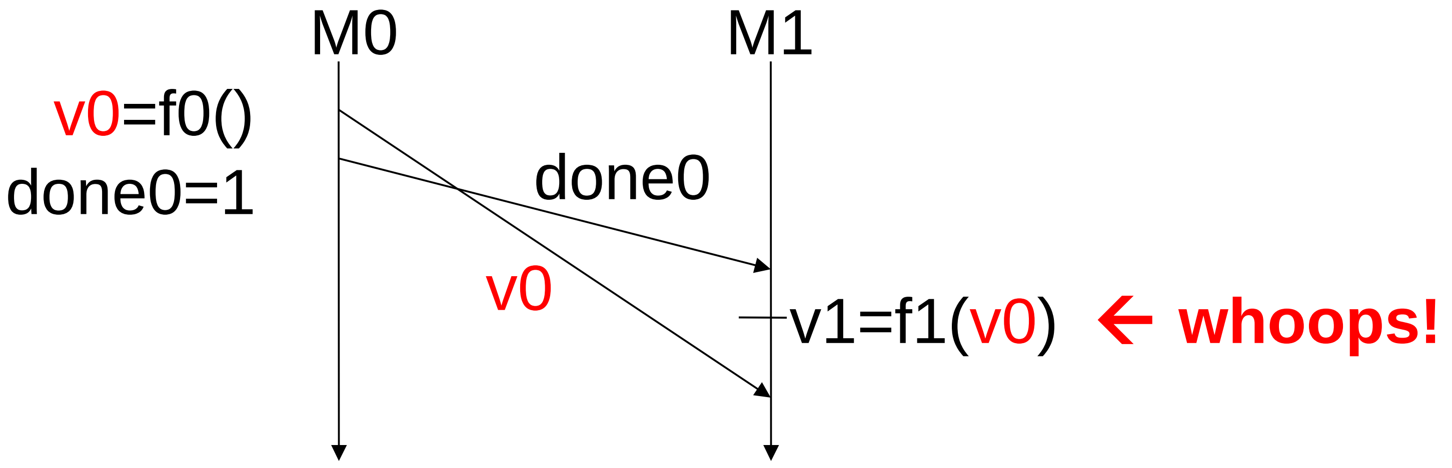


- Each machine has a local copy of all of memory
- Operations:
  - **Read**: from local memory
  - **Write**: send update msg to each host (but **don't wait**)
- Fast: never waits for communication

Question: Does this DSM work well for our application?

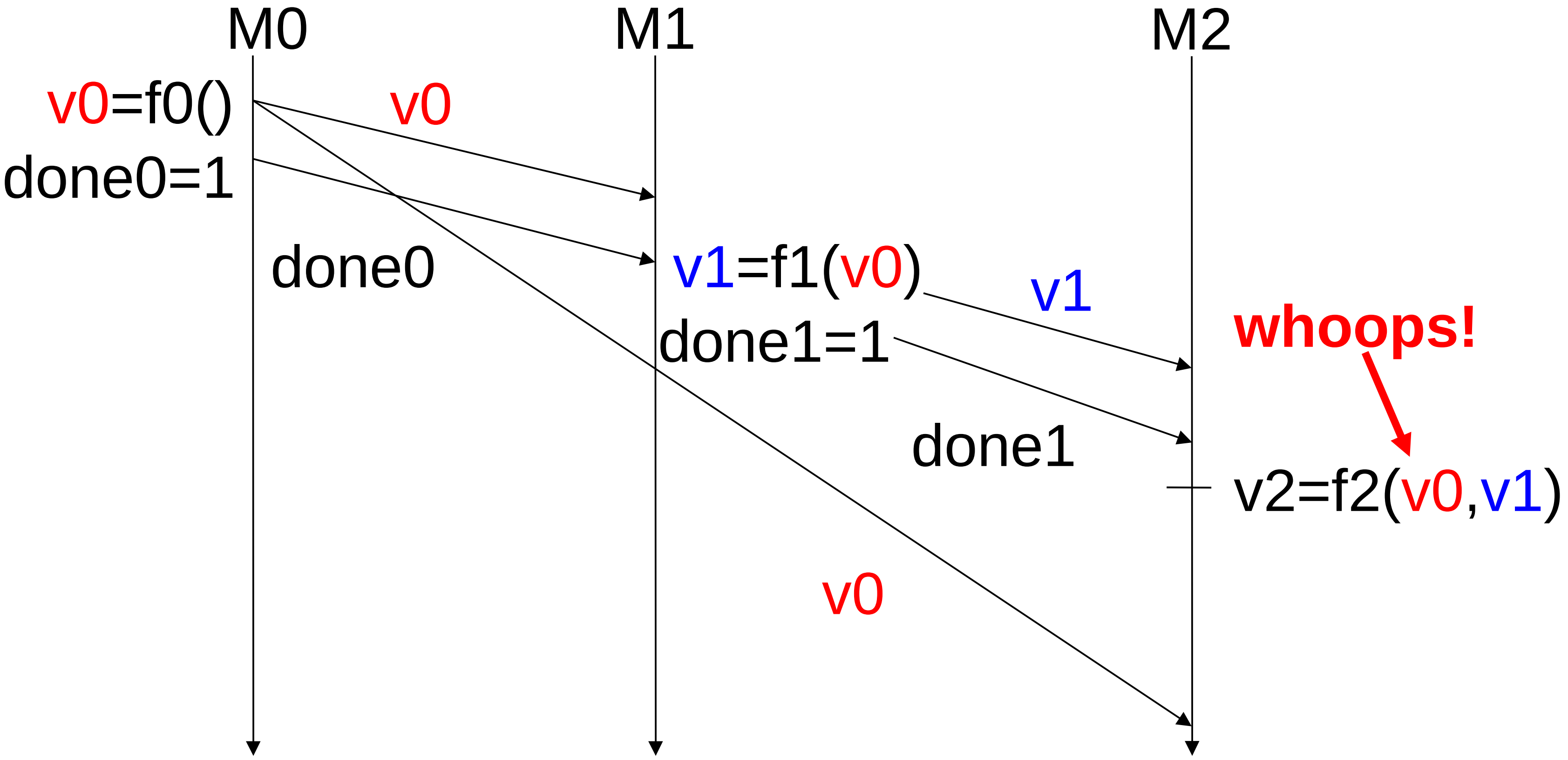
Problem 1 with Naïve DSM

- M0's v0=… and done0=… may be interchanged by network, leaving v0 unset but done0=1



Problem 2 with Naïve DSM

- M2 sees M1's writes before M0's writes
  - I.e. M2 and M1 disagree on order of M0 and M1 writes



Naïve DSM Properties

- Naïve DSM is fast but has unexpected behavior

- Clearly, it's not sequentially consistent
  - So, how do we make it so, and what do we lose in performance because of that?

Sequential Consistency

- Rules: There exists a total ordering of ops s.t.
  - Rule 1: Each machine's own ops appear in order
  - Rule 2: All machines see results according to total order (i.e. reads see most recent writes)

- We say that any runtime ordering of operations (also called a *history*) can be "explained" by a sequential ordering of operations that follows the above two rules

Does Seq. Consistency Avoid Problems?

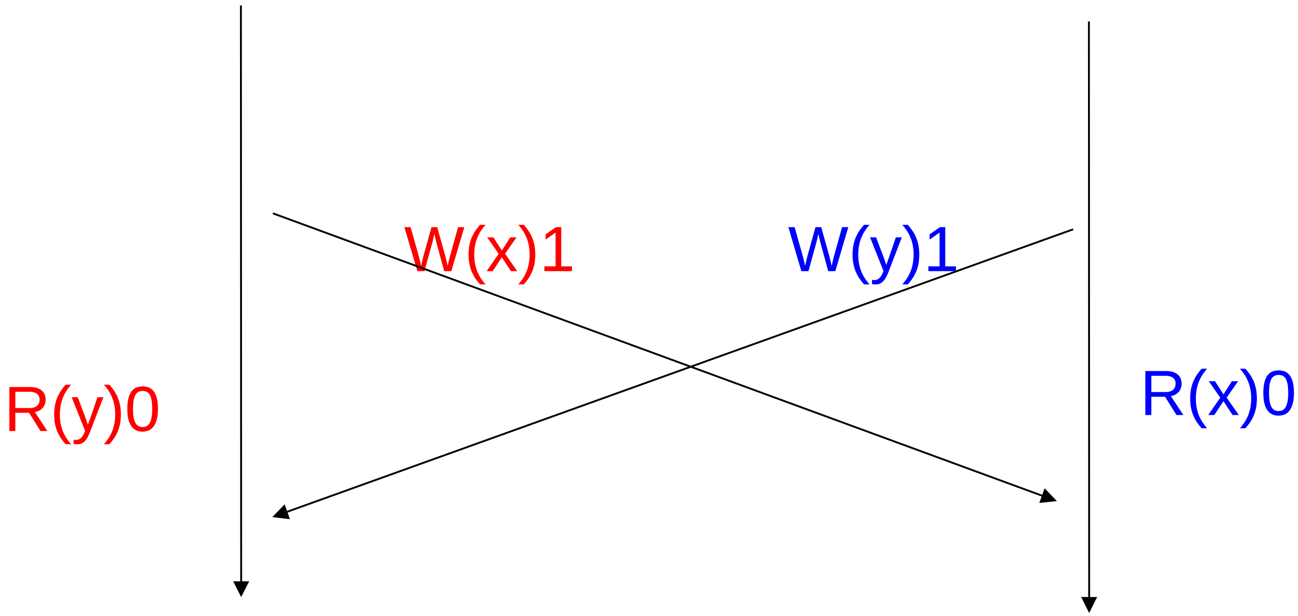
- There is a total ordering of events s.t.:
  - Rule 1: Each machine's own ops appear in order
  - Rule 2: All machines see results according to total order
- Problem 1: Can M1 ever see v0 unset but done0=1?
  - M0's execution order was v0=… done0=…
  - M1 saw done0=… v0=…
  - Each machine's operations must appear in execution order so cannot happen w/ sequential consistency
- Problem 2: Can M1 and M2 disagree on ops' order?
  - M1 saw v0=… done0=… done1=…
  - M2 saw done1=… v0=…
  - This cannot occur given a single total ordering

Seq. Consistency Implementation Requirements

1. Each processor issues requests in the order specified by the program
   - Do not issue the next request unless the previous one has finished

2. Requests to an individual memory location are served from a single FIFO queue
   - Writes occur in a single order
   - Once a read observes the effect of a write, it's ordered behind that write

Naive DSM violates R1,R2



- Read from local state
- Send writes to the other nodes, but do not wait

R1: a processor issues read before waiting for write to complete
R2: 2 processors issue writes concurrently, no single order

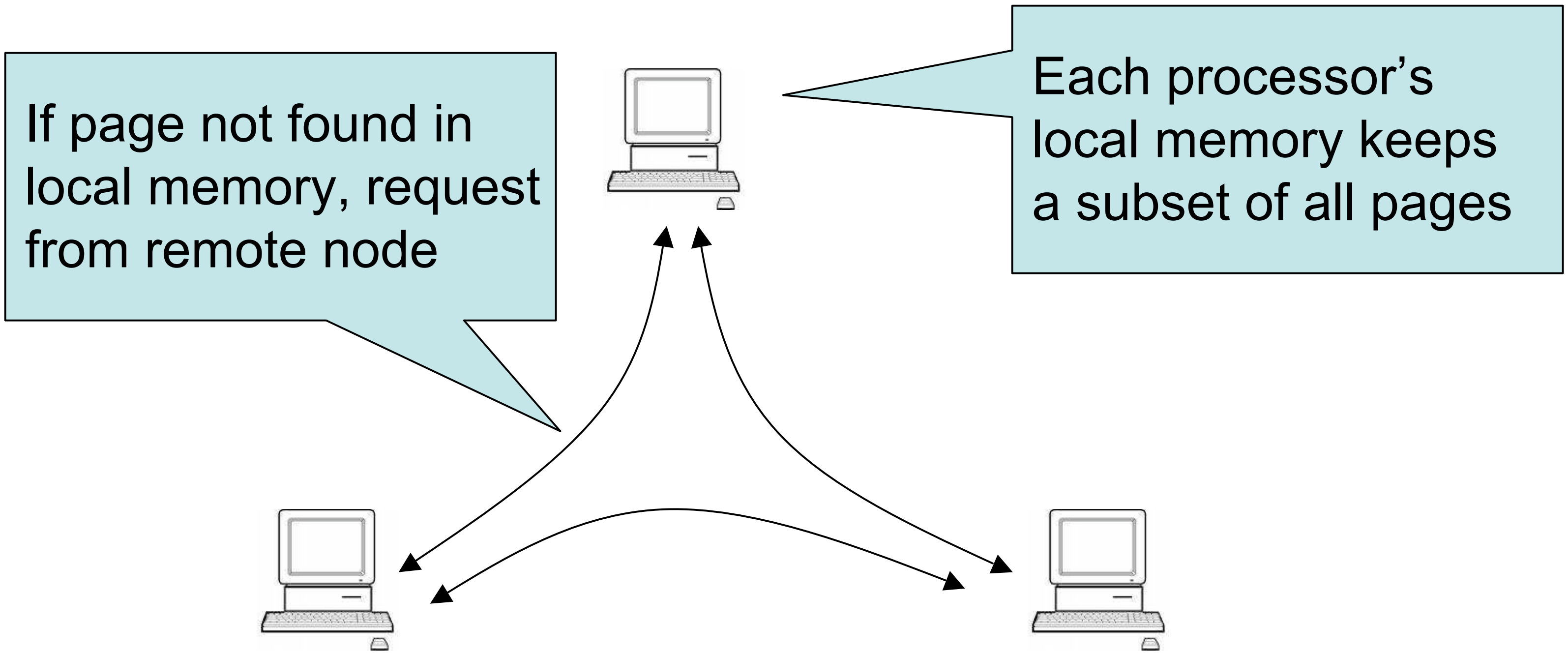
Case Study:

Ivy: Integrated shared virtual memory at Yale

Ivy distributed shared memory

- What does Ivy do?
  - Provide a shared memory system across a group of workstations
- Why shared memory?
  - Easier to write parallel programs with than using message passing
  - We'll come back to this choice of interface in later lectures

Ivy architecture



- Each node caches read pages
  - Why?
- Can a node directly write cached pages?

Ivy aims to provide sequential consistency

- How?
  - Always read a fresh copy of data
    - Must invalidate all cached pages before writing a page.
    - This simulates the FIFO queue for a page because once a page is written, all future reads must see the latest value
  - Only one processor (owner) can write a page at a time

Ivy implementation

- The ownership of a page moves across nodes
  - Latest writer becomes the owner
  - Why?
- Challenge:
  - how to find the owner of a page?
  - how to ensure one owner per page?
  - How to ensure all cached pages are invalidated?

Ivy: centralized manager

manager

Page#, copy_set, owner
p1, {..}, {A}

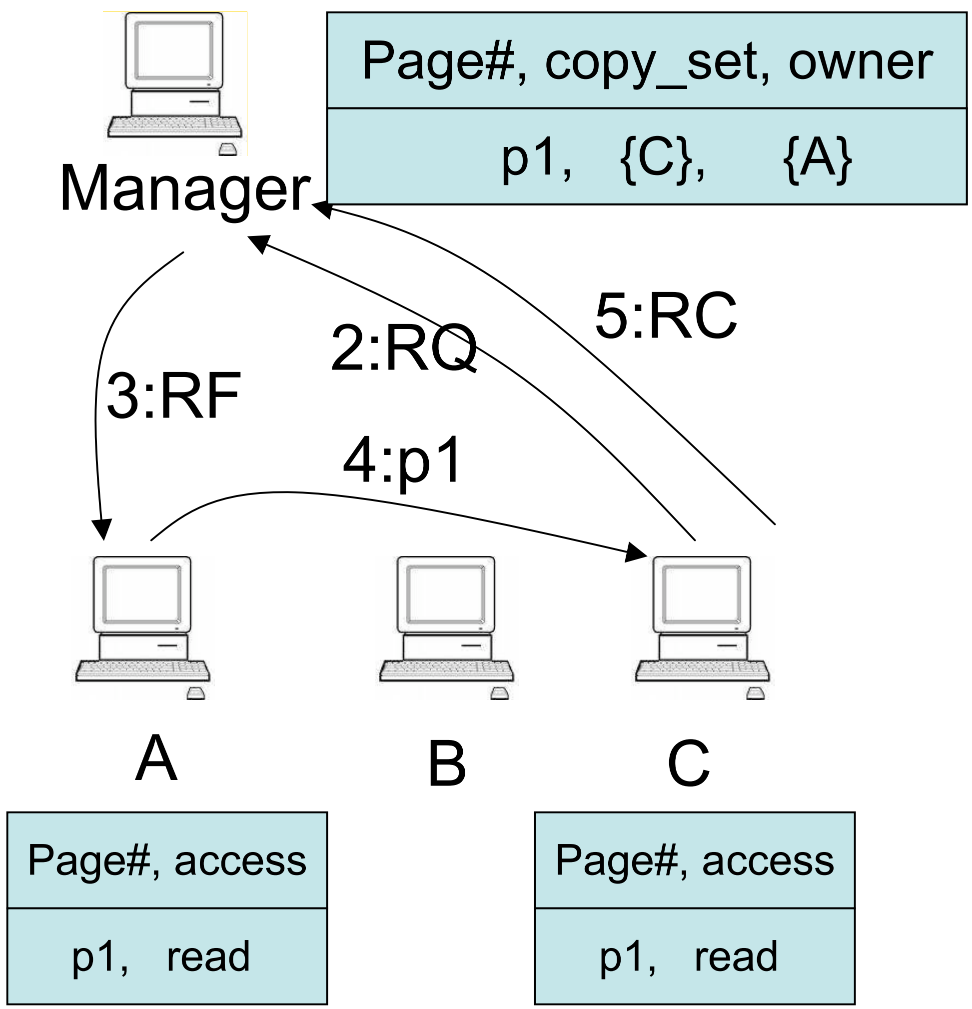
Page#, access
p1, read

A

B

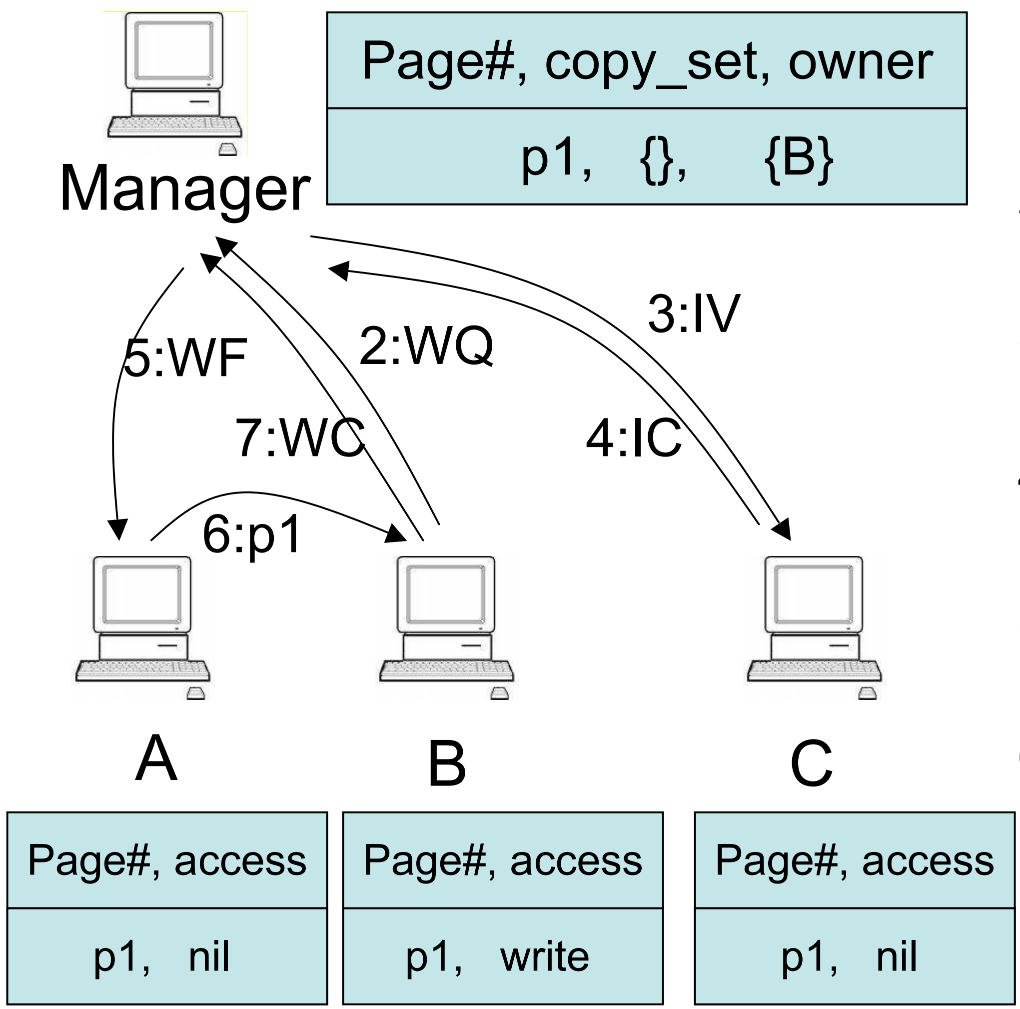
C

Ivy: read



1. Page fault for p1 on C
2. C sends RQ(read request) to M
3. M sends RF(read forward) to A, M adds C to copy_set
4. A sends p1 to C, C marks p1 as read-only
5. C sends RC(read confirmation) to M

Ivy: write



1. Page fault for p1 on B
2. B sends WQ(write request) to M
3. M sends IV(invalidate) to copy_set = {C}
4. C sends IC(invalidate confirm) to M
5. M clears copy_set, sends WF(write forward) to A
6. A sends p1 to B, clears access
7. B sends WC(write confirmation) to M

Ivy invariants?

- Every page has exactly one current owner
- Current owner has a copy of the page
- If mapped r/w by owner, no other copies
- If mapped r/o by owner, identical to other copies
- Manager knows about all copies

Is Ivy Sequentially Consistent?

- Well, yes, but we’re not gonna prove it…
- Proof sketch:
  - Proof by contradiction that there is a schedule that cannot be explained by any sequential ordering that satisfies the two rules
  - This means that there are operations in the schedule that break one of the two rules
  - Reach contradiction on each of the two rules by using definition of reads/writes in Ivy
- For simplicity, let’s look instead at why Ivy doesn’t have the two problems we’ve identified for naïve DSM

Eventual Consistency (Overview)

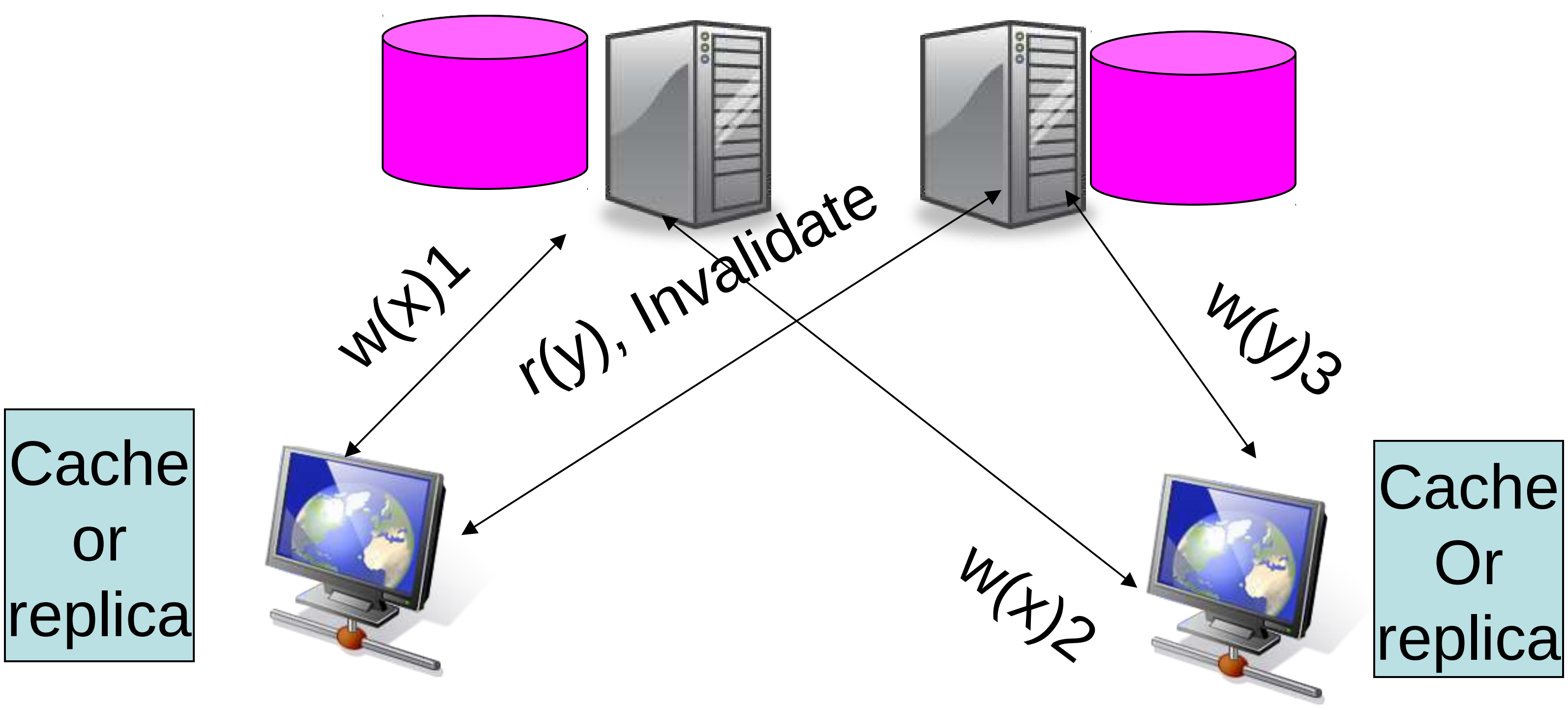
- Allow stale reads, but ensure that reads will eventually reflect previously written values
  - Even after very long times
- Doesn't order concurrent writes as they are executed, which might create conflicts later: which write was first?
- Used in Amazon's Dynamo, a key/value store
  - Plus a lot of academic systems
  - Plus file synchronization ← familiar example, we'll use this

Why Eventual Consistency?

- More concurrency opportunities than strict, sequential, or causal consistency
- Sequential consistency requires highly available connections
  - Lots of chatter between clients/servers
- Sequential consistency many be unsuitable for certain scenarios:
  - Disconnected clients (e.g. your laptop goes offline, but you still want to edit your shared document)
  - Network partitioning across datacenters
  - Apps might prefer potential inconsistency to loss of availability

Case-in-Point:
Realizing Sequential Consistency

- All reads/writes to address X must be ordered by one memory/storage module responsible for X (see Ivy, Lec10)
- If you write data that others have, you must let them know
- Thus, everyone must be online all the time



Why (Not) Eventual Consistency?

- ✓ Support disconnected operations or network partitions
  - Better to read a stale value than nothing
  - Better to save writes somewhere than nothing
- ✓ Support for increased parallelism
  - But that's not what people have typically used this for
- ☒ Potentially anomalous application behavior
  - Stale reads and conflicting writes…

Sequential vs. Eventual Consistency

- Sequential: pessimistic concurrency handling
  - Decide on update order as they are executed
- Eventual: optimistic concurrency handling
  - Let updates happen, worry about deciding their order later
  - May raise conflicts
    - Think about when you code offline for a while – you may need to resolve conflicts with other teammembers when you commit
    - Resolving conflicts is not that difficult with code, but it's really hard in general (e.g., think about resolving conflicts when you've updated an image)

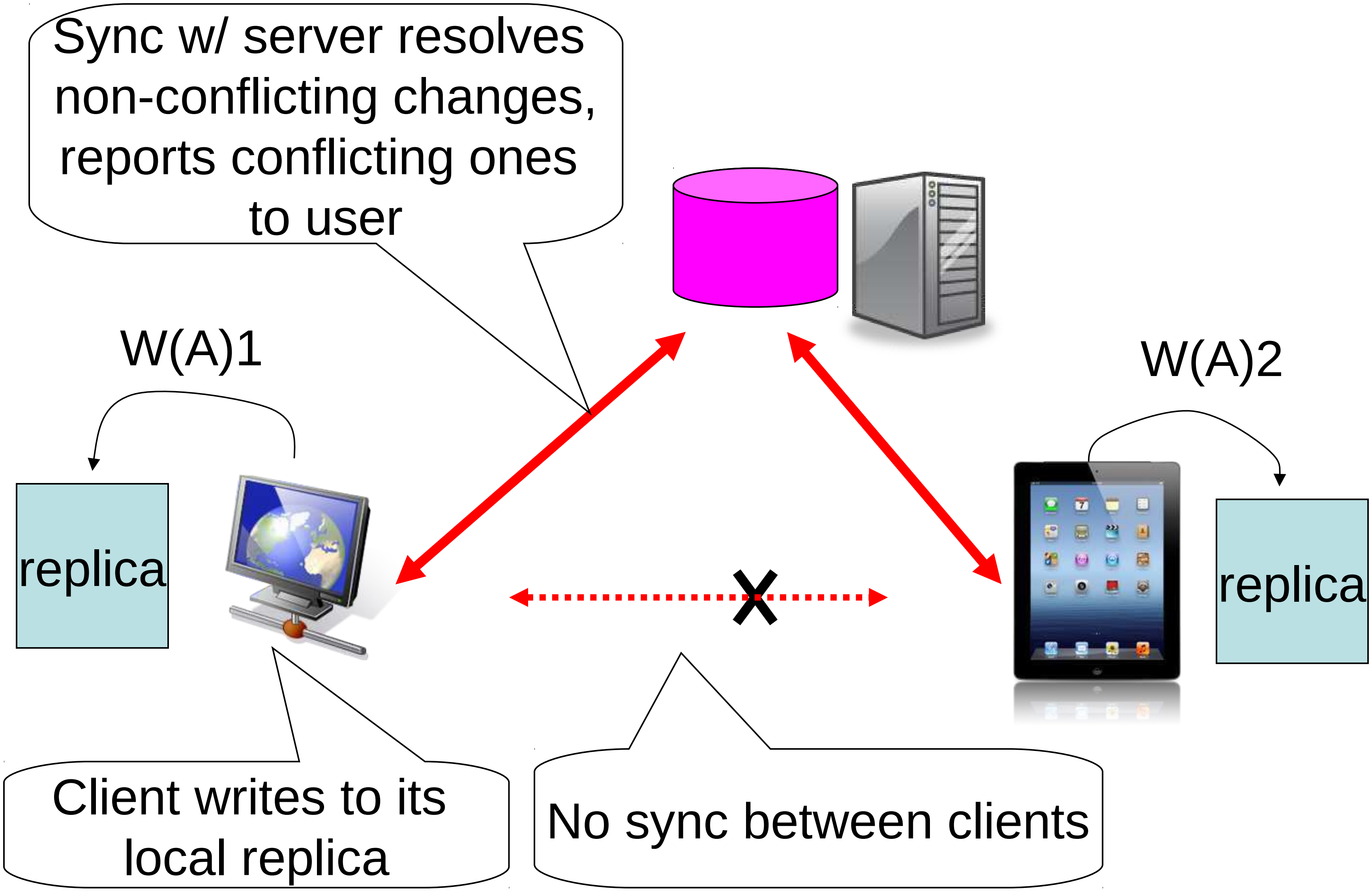
Example Usage: File Synchronizer

- One user, many gadgets, common files (e.g., contacts)

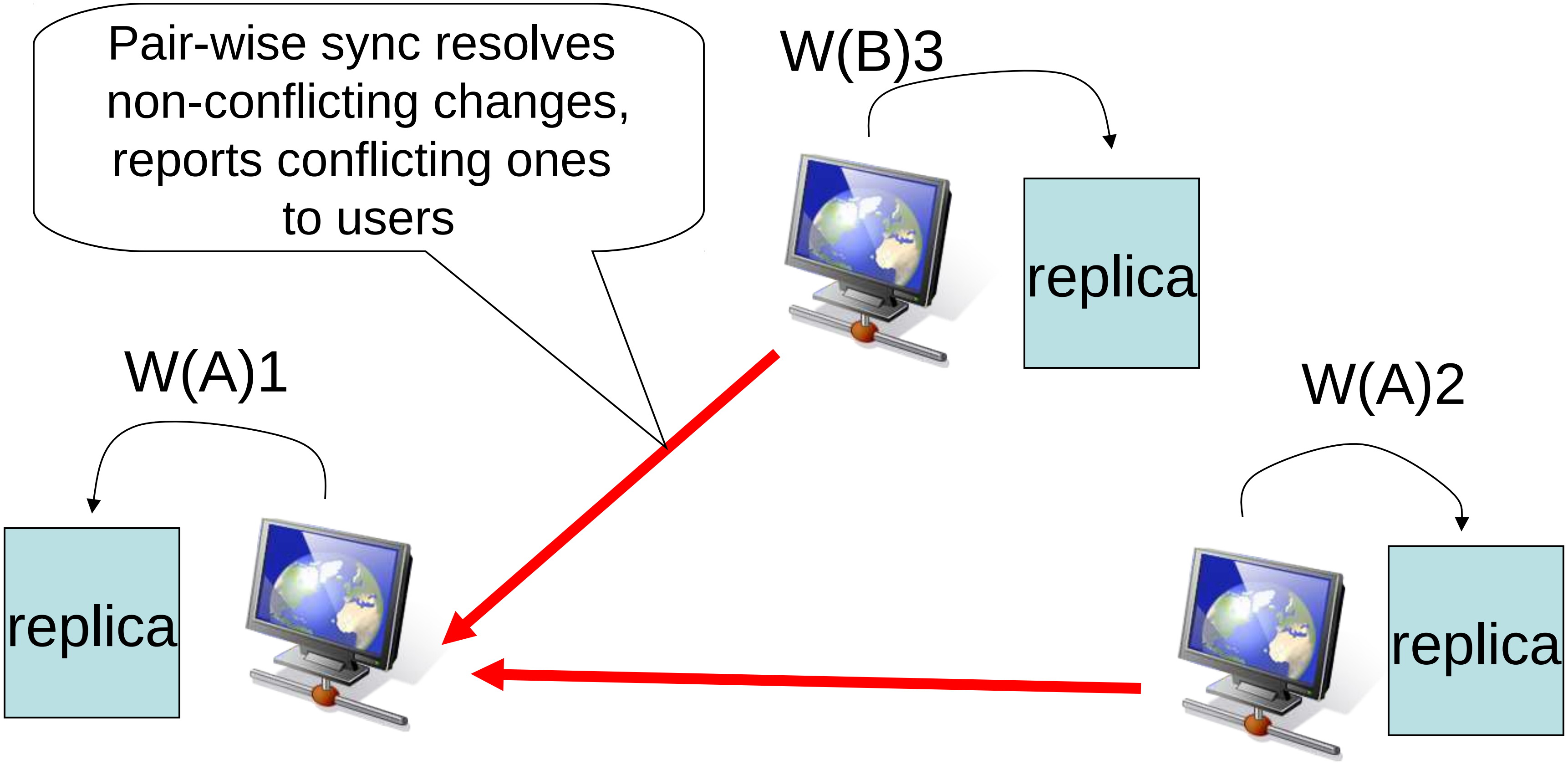



- Goal of file synchronization
  1. All replica contents eventually become identical
  2. No lost updates
     - Do not replace new version with old ones

Operating w/o Total Connectivity



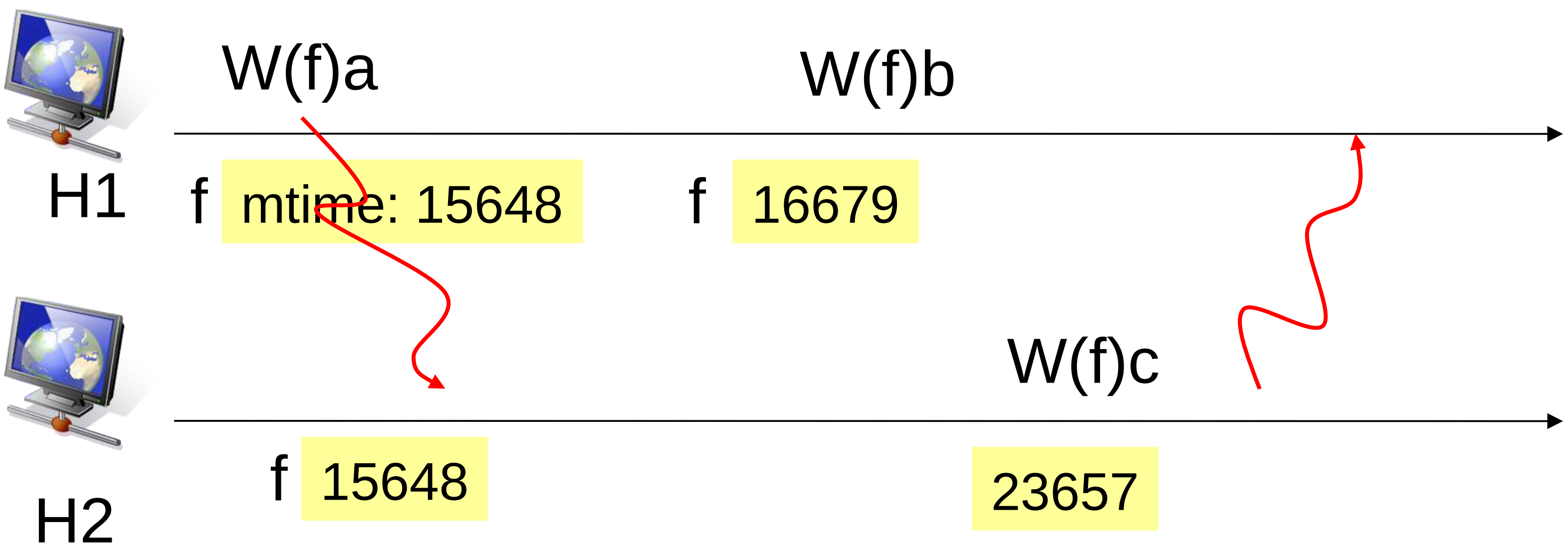
Pair-wise Synchronization



Prevent lost updates

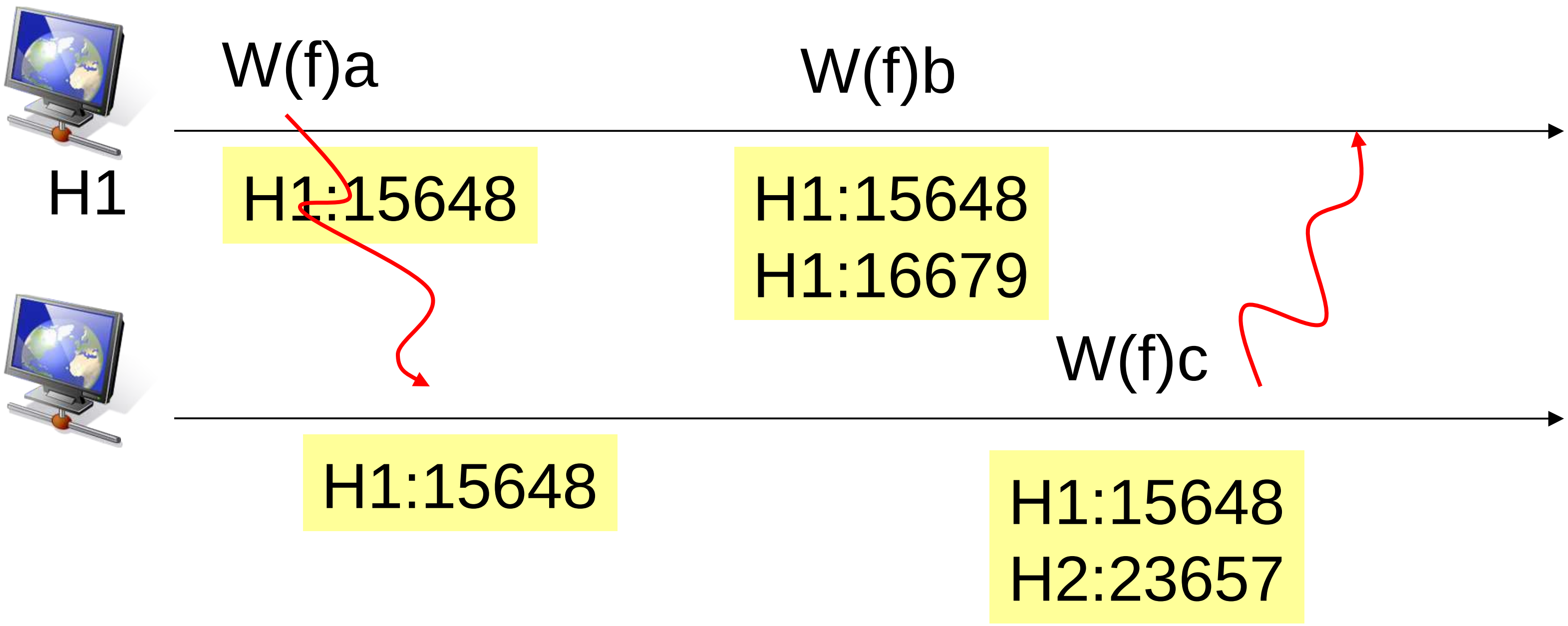
- Detect if updates were sequential
  - If so, replace old version with new one
  - If not, detect conflict

How to Prevent Lost Updates?



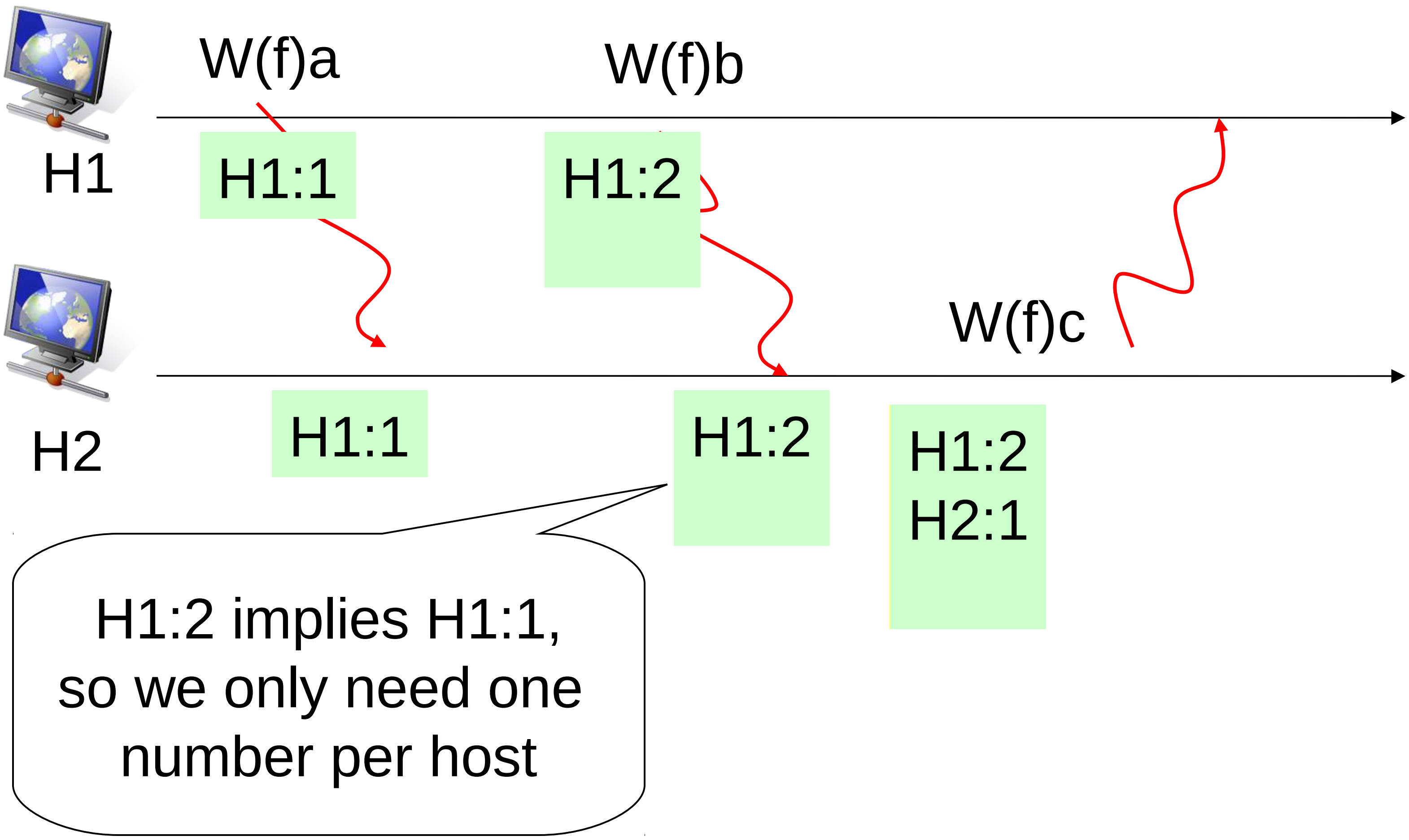
- Strawman: use mtime to decide which version should replace the other
- Problems?
  1. If clocks are unsynchronized: new data might have older timestamp than old data
  2. Does not detect conflicts => may lose some contacts…

Strawman Fix



- Carry the entire modification history (a log)
- If history X is a prefix of Y, Y is newer
- If it’s not, then detect and potentially solve conflicts

Compress Version History



How to Deal w/ Conflicts?

- Easy: mailboxes w/ two different set of messages
- Medium: changes to different lines of a C source file
- Hard: changes to same line of a C source file

- After conflict resolution, add a new item to the history?

So, What's Used Where?

- Sequential consistency
  - A number of both academic and industrial systems provide (at least) sequential consistency (some a bit stronger – linearizability)
  - Examples: Yale's IVY DSM, Microsoft's Niobe DFS, Cornell's chain replication, …
- Causal consistency – Promiscuous, many other DB replication systems
- Eventual consistency
  - Very popular for a while both in industry and in academia
  - Examples: file synchronizers, Amazon's Dynamo, Bayou

Many Other Consistency Models Exist

- Other standard consistency models
  - Linearizability
  - Serializability
  - Monotonic reads
  - Monotonic writes
  - … read Tanenbaum 7.3 if interested (these are not required for exam)

- In-house consistency models:
  - AFS's close-to-open
  - GFS's atomic at-most-once appends