Distributed Systems

Lec 11: Consistency Models

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(http://pdos.csail.mit.edu/6.824/notes/l06.txt, http://www.news.cs.nyu.edu/~jinyang/fa09/notes/ds-consistency.pdf)

Reminder: Distributed File Systems

- We discussed about three: NFS, AFS, GFS
- Each has its own design, which is oriented toward a particular workload and requirements
- Each trades a form of consistency for performance and scale
  - Remember consistency properties for NFS/AFS/GFS?
  - Remember some mechanisms by which they achieve these?

Reminder: Distributed File Systems

- We discussed about three: NFS, AFS, GFS
- Each has its own design, which is oriented toward a particular workload and requirements
- Each trades a form of consistency for performance and scale
  - AFS: close-to-open semantic
  - NFS: periodic refreshes, close-to-open semantic
  - GFS: atomic-at-least-once record appends

today

But how do these compare? What's "right"?

What do these mean for applications/users?

We need some baselines to judge…

Example: GFS Consistency

- GFS provides:
  - Hardly any guarantees for normal writes
  - At-least-once atomic appends

- Record Appends:
  - The client specifies only the data, not the file offset
  - If record fits in chunk, primary chooses the offset and communicates it to all replicas → *offset is arbitrary*
  - If record doesn't fit in chunk, the chunk is padded → *file may have blank spaces*
  - If a record append fails at any replica, the client retries the operation → *file may contain record duplicates*

Implications for Applications

- GFS' consistency is not completely intuitive or generally applicable

- Applications must adapt to its weak semantics – how?
  - Rely on appends rather on overwrites
  - Write self-validating records
    - Checksums to detect and remove *padding*
  - Write self-identifying records
    - Unique Identifiers to identify and discard *duplicates*

- Hence, programmers need be very careful!
  - And applications need be amenable for weak semantics

Today: Consistency Models

- We'll look at "standard" consistency models
  - Properties we wish we'd have, or that are generally applicable and well understood

- Today: strong consistency models
  - Strict consistency, sequential consistency

- Next time: weaker consistency models
  - Causal consistency, eventual consistency

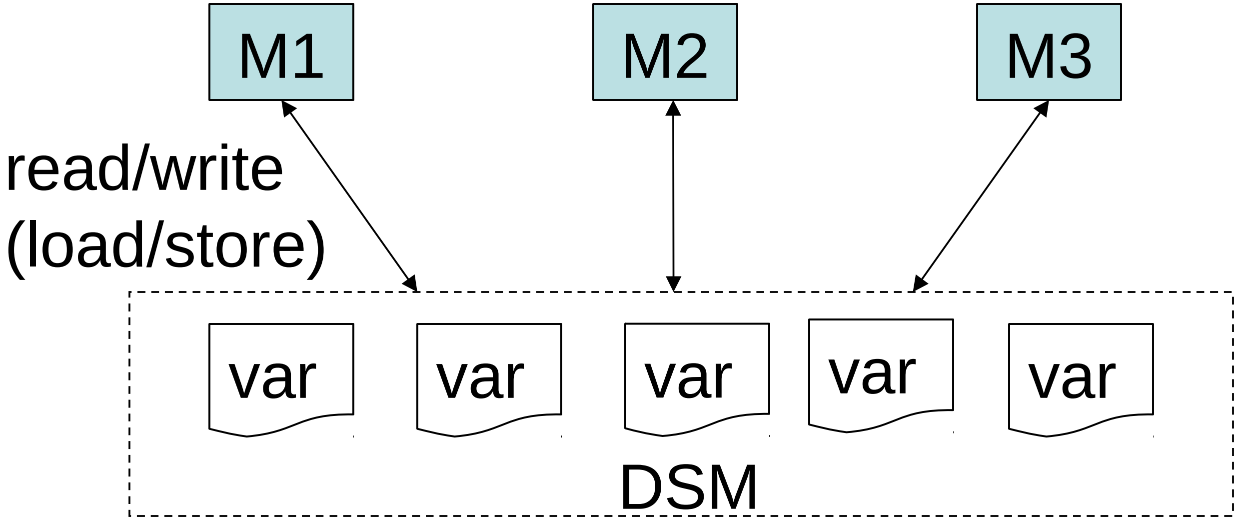
  - We'll relate NFS/AFS/GFS' models to those "baseline" models

What Is Consistency?

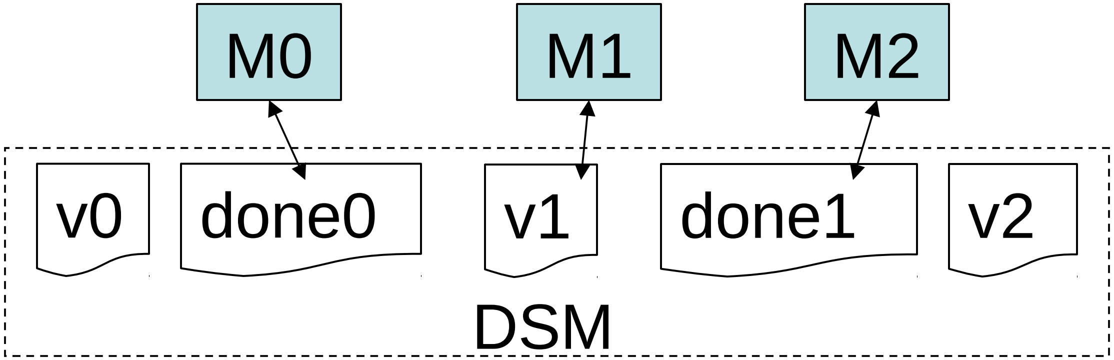
- Consistency = meaning of concurrent reads and writes on shared, possibly replicated, state
- As you've seen, it's a huge factor in many designs
- Choice trades off performance/scalability vs. programmer-friendliness
- Today we'll look at one case study: distributed shared memory
  - Concepts are similar to those in distributed storage systems, though

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:

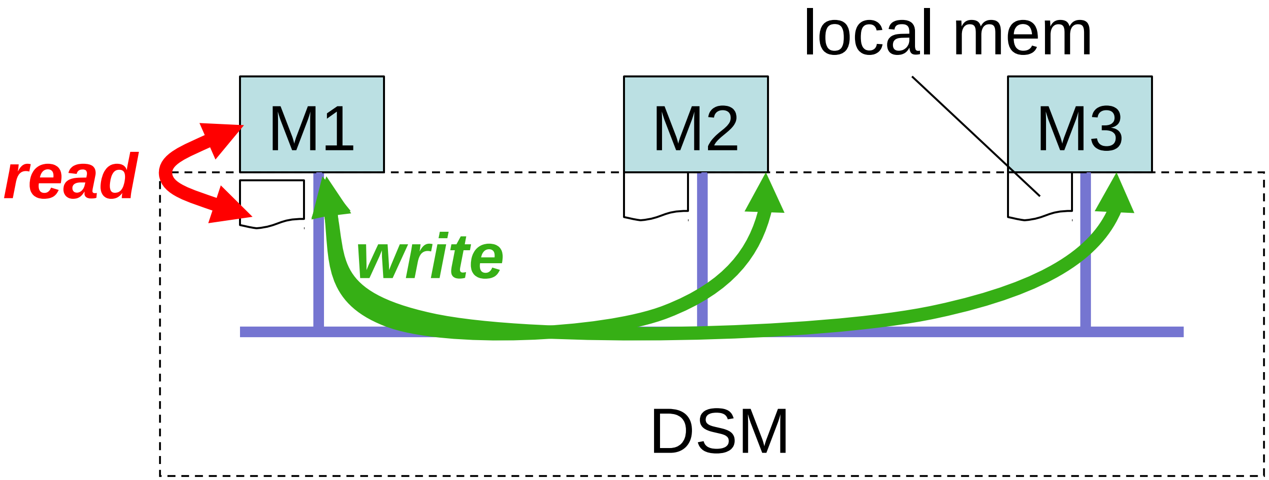
```
while (done0 == 0)
    ;
v1 = f1(v0);
done1 = 1;
```

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

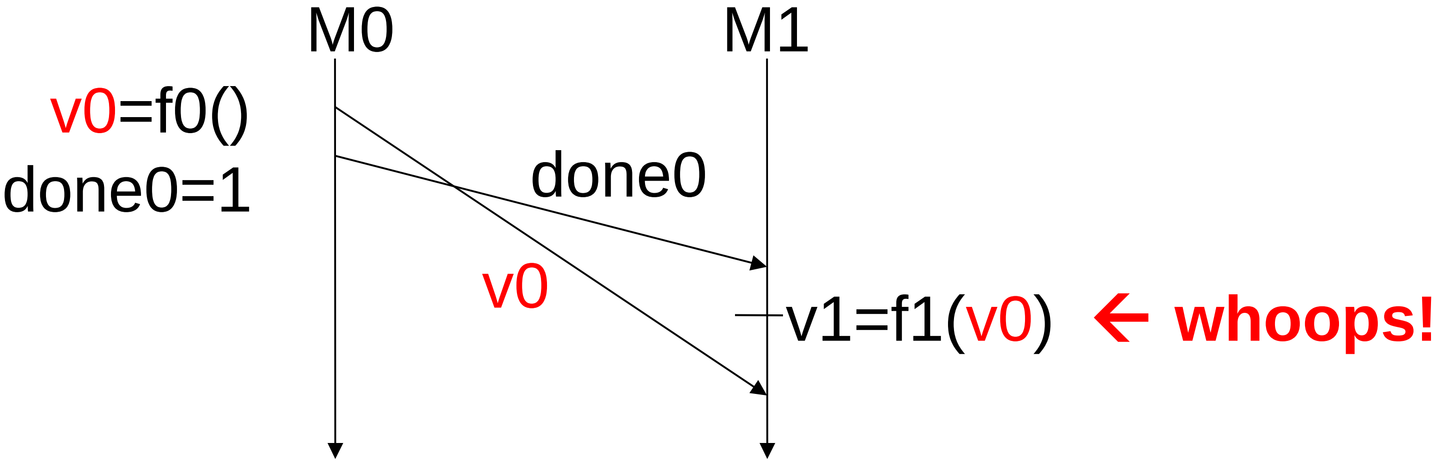


- Each machine has a local copy of all of memory
- Operations:
  - **Read**: from local memory
  - **Write**: send update msg to each host (but **don't wait**)
- Fast: never waits for communication

Question: Does this DSM work well for our application?

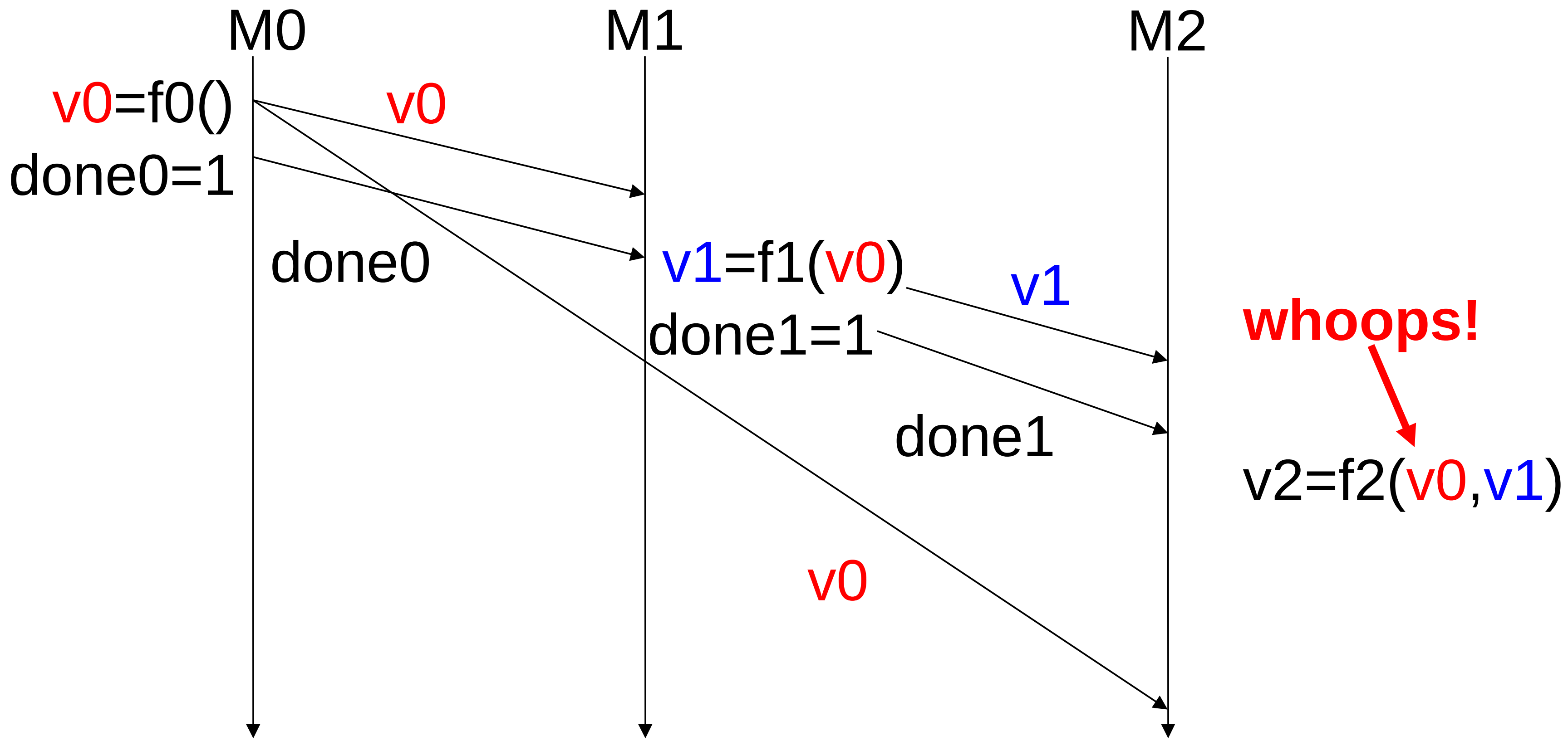
Problem 1 with Naïve DSM

- 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

- Naive DSM is fast but has unexpected behavior

- Maybe DSM isn't “correct”
- Or maybe we should have never expected the example application to work as we did
  - I.e., maybe we need to fix the app, not the DSM…

Consistency Models

- Memory system promises to behave according to certain rules, which constitute the system’s “consistency model”
  - We write programs assuming those rules

- The rules are a “contract” between memory system and programmer

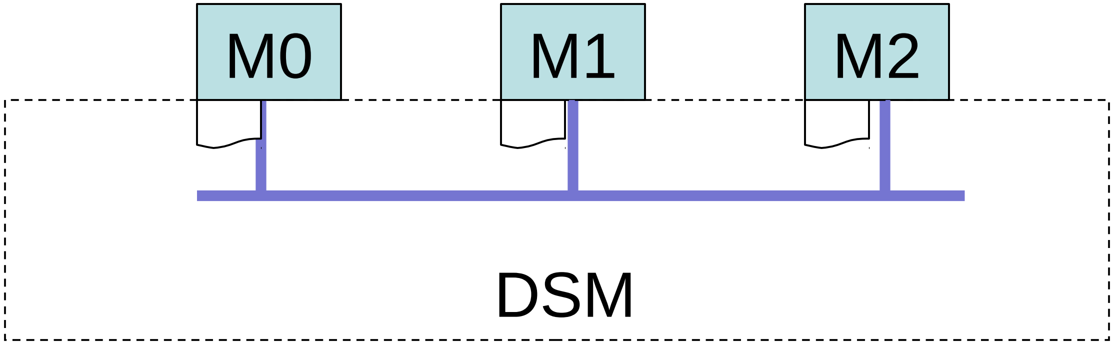
Challenges

- No right or wrong consistency models
  - Tradeoff between ease of programmability and efficiency
  - E.g. what’s the consistency model for web pages?
  - What should it be for a shared memory system?

- Consistency is hard in (distributed) systems:
  - Data replication (caching)
  - Concurrency
  - Failures

Model 1: Strict Consistency

- Each operation is stamped with a global wall-clock time
- Rules:
  - Rule 1: Each read gets the latest written value
  - Rule 2: All operations at one CPU are executed in order of their timestamps



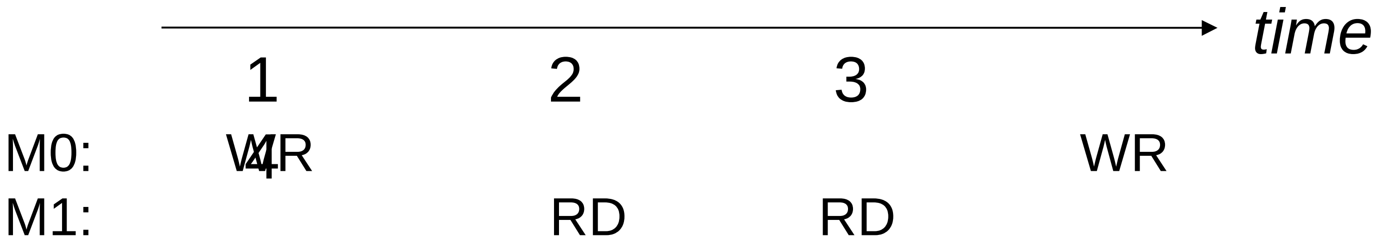
Does Strict Consistency Avoid Problems?

- Suppose we implement rules, can we still get problems?
  - Rule 1: Each read gets the latest written value
  - Rule 2: All operations at one CPU are executed in order of their timestamps

- Problem 1: Can M1 ever see v0 unset but done0=1?
- Problem 2: Can M1 and M2 disagree on order of M0 and M1 writes?

- So, strict consistency has very intuitive behavior
  - Essentially, the same semantic as on a uniprocessor!
- But how to implement it efficiently?
  - Without reducing distributed system to a uniprocessor…

Implementing Strict Consistency



- To achieve, one would need to ensure:
  - – Each read must be aware of, and wait for, each write
    - RD@2 aware of WR@1; WR@4 must know how long to wait…
  - – Real-time clocks are strictly synchronized…
- Unfortunately:
  - – Time between instructions << speed-of-light…
  - – Real-clock synchronization is tough (pre-2012 ☺)
- So, strict consistency is tough to implement efficiently

Model 2: Sequential Consistency

- Slightly weaker model than strict consistency
  - Most important difference: doesn’t assume real time

- 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 Is Easier To Implement Efficiently

- No notion of real time
- System has some leeway in how it interleaves different machines' ops
  - Not forced to order by op start time, as in strict consistency

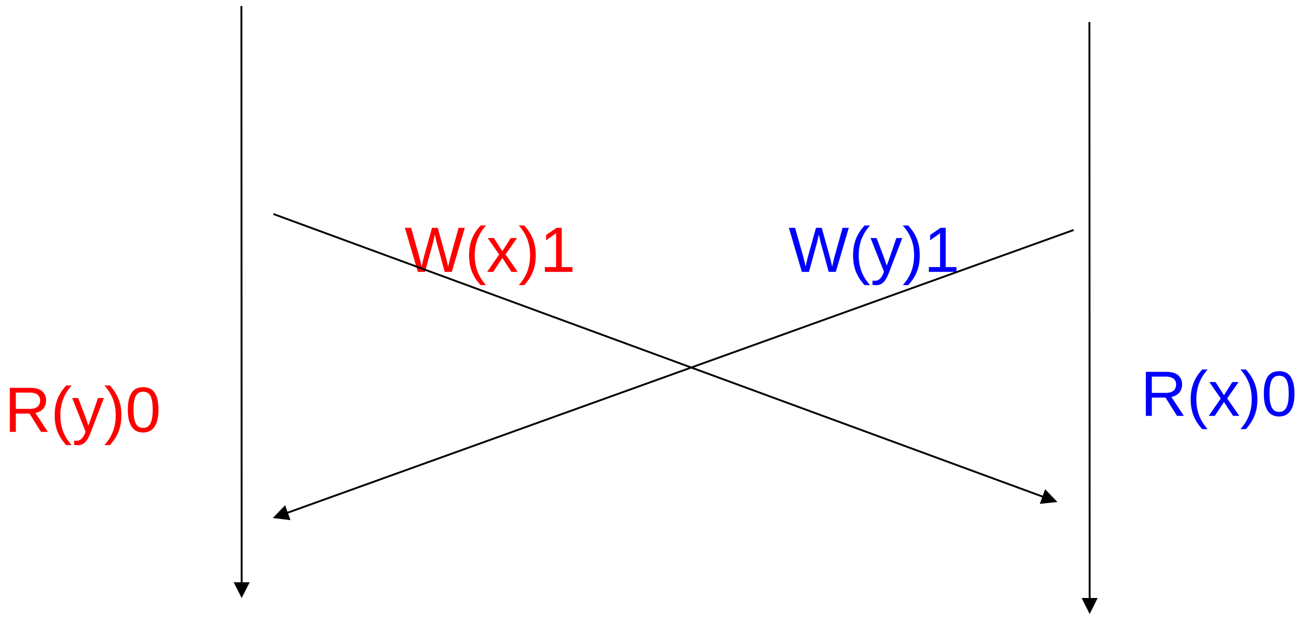
- Performance is still not great
  - Once a machine's write completes, other machines' reads must see new data
  - Thus communication cannot be omitted or much delayed
  - Thus either reads or writes (or both) will be expensive

Sequential Consistency 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

1. Requests to an individual memory location (storage object) 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 node, but do not wait

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

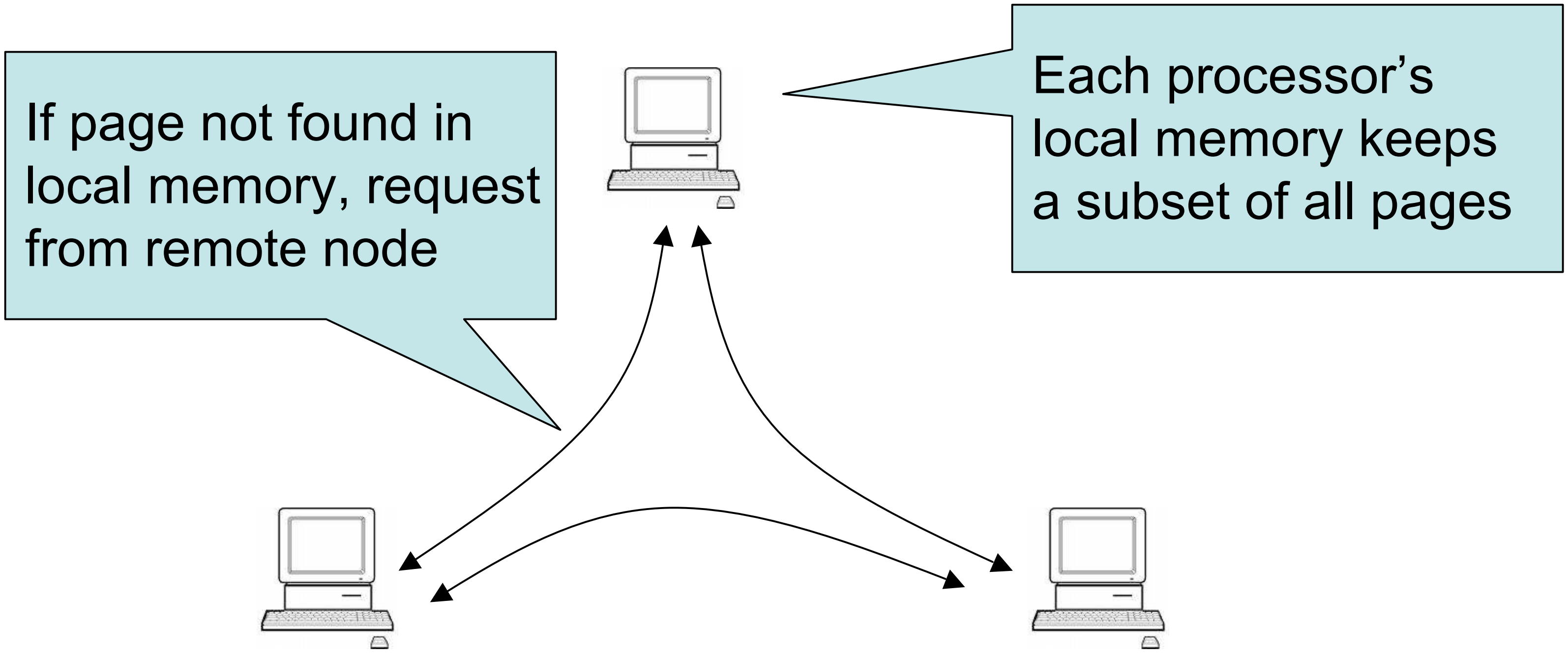
Case Study:

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



If page not found in local memory, request from remote node

Each processor's local memory keeps a subset of all pages

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

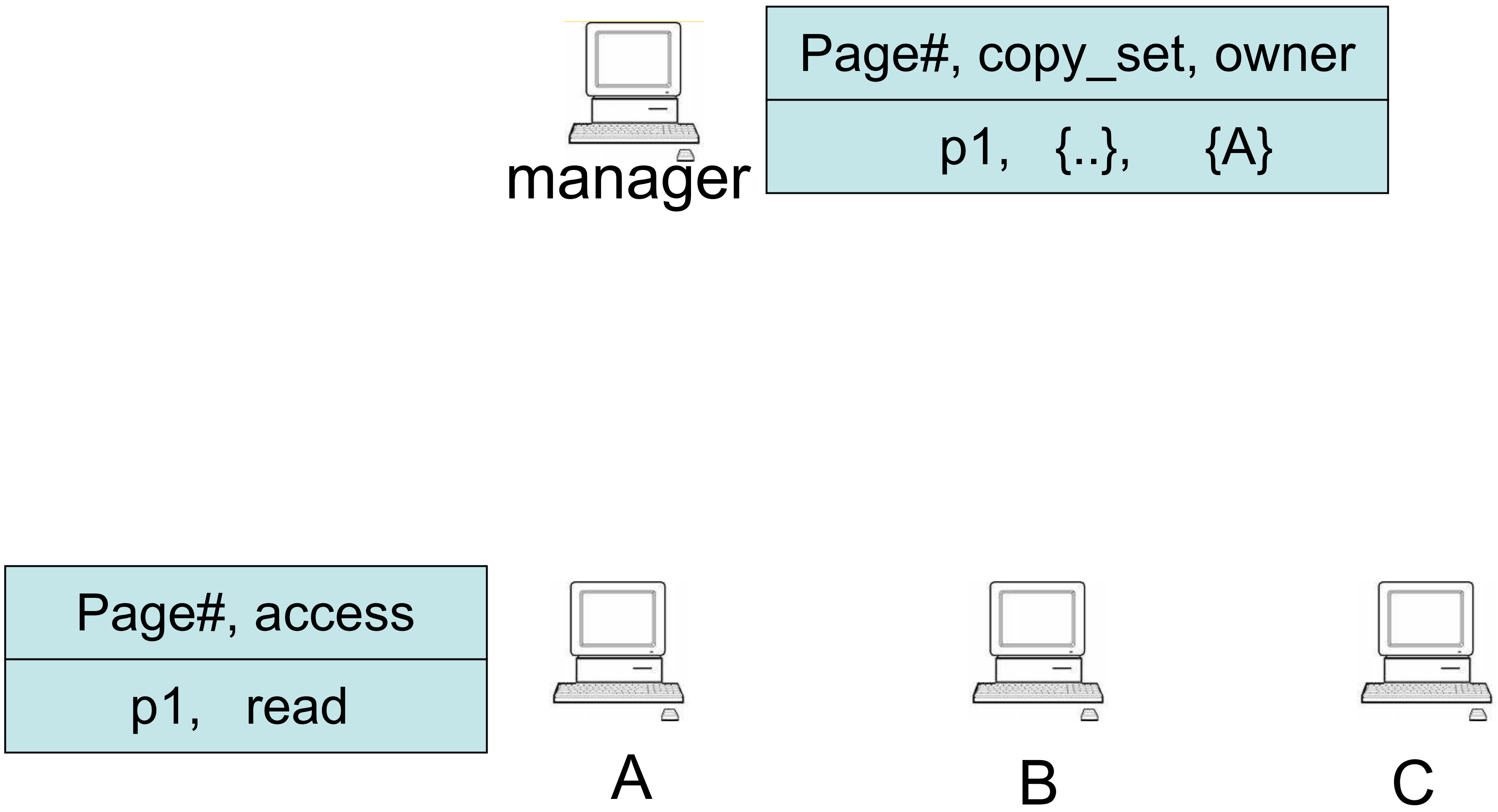
Ivy aims to provide sequential consistency

- 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?

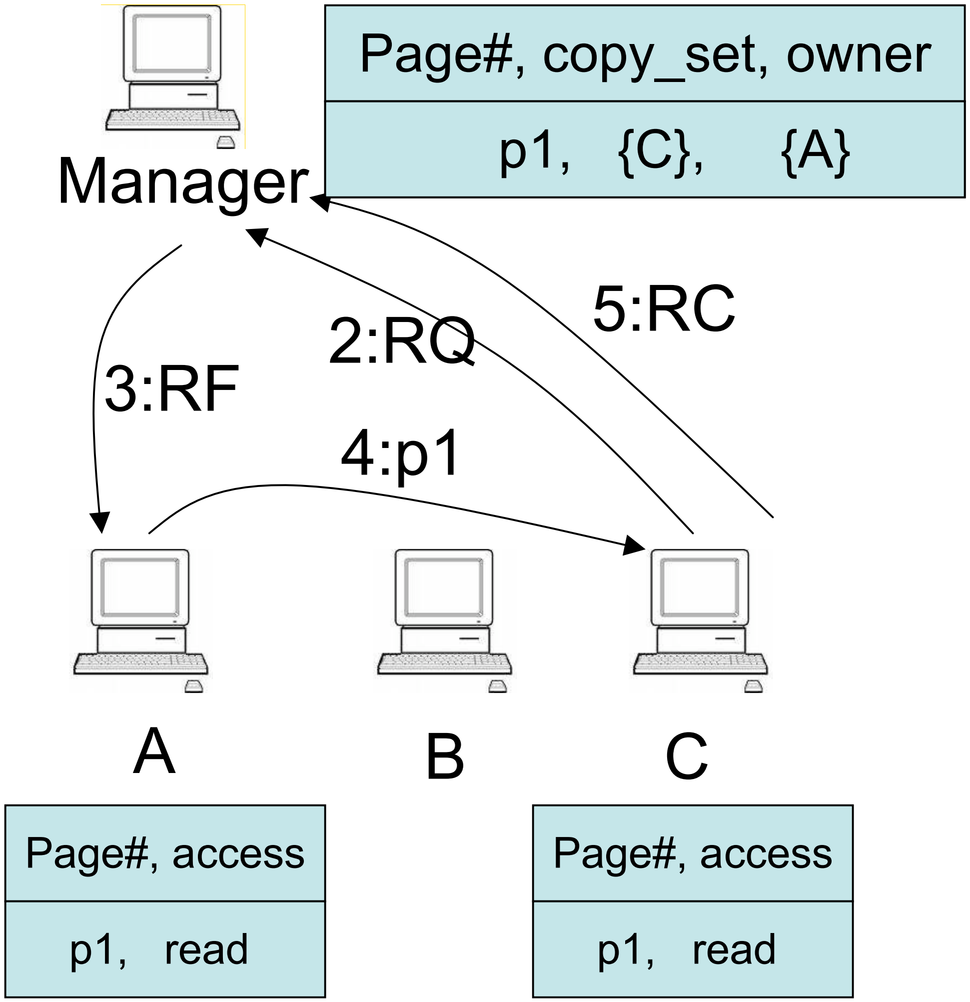
Ivy: centralized manager



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

Page#, access
p1, read

Ivy: read



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

A:

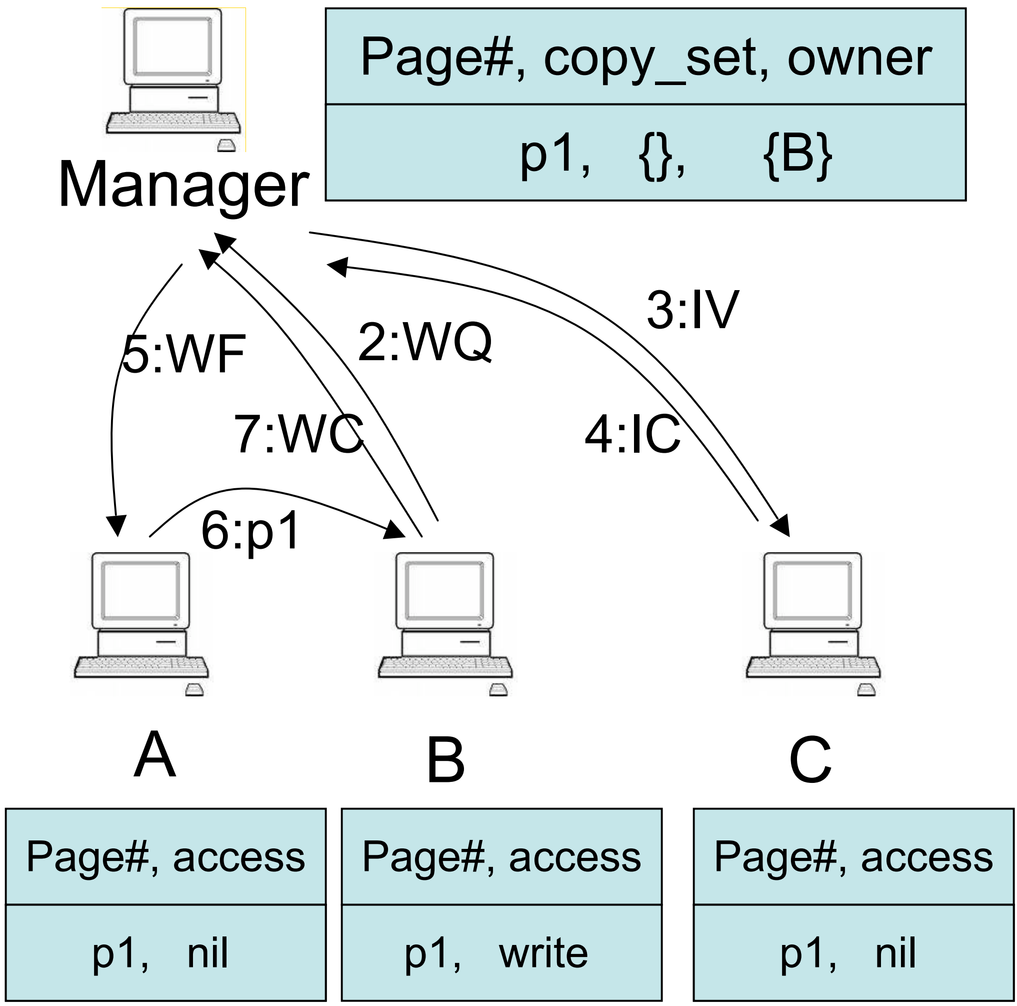
Page#, access	
p1,	read

C:

Page#, access	
p1,	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



Page#, copy_set, owner		
p1,	{},	{B}

A

Page#, access	
p1,	nil

B

Page#, access	
p1,	write

C

Page#, access	
p1,	nil

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