DIRECTORY COHERENCE

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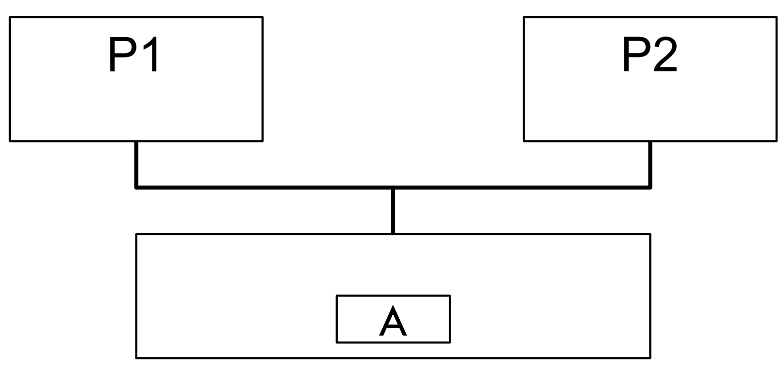
Overview

- Upcoming deadline
  - Tonight: project proposal
- This lecture
  - Snooping wrap-up
  - Directory coherence
  - Implementation challenges
  - Token-based coherence protocol

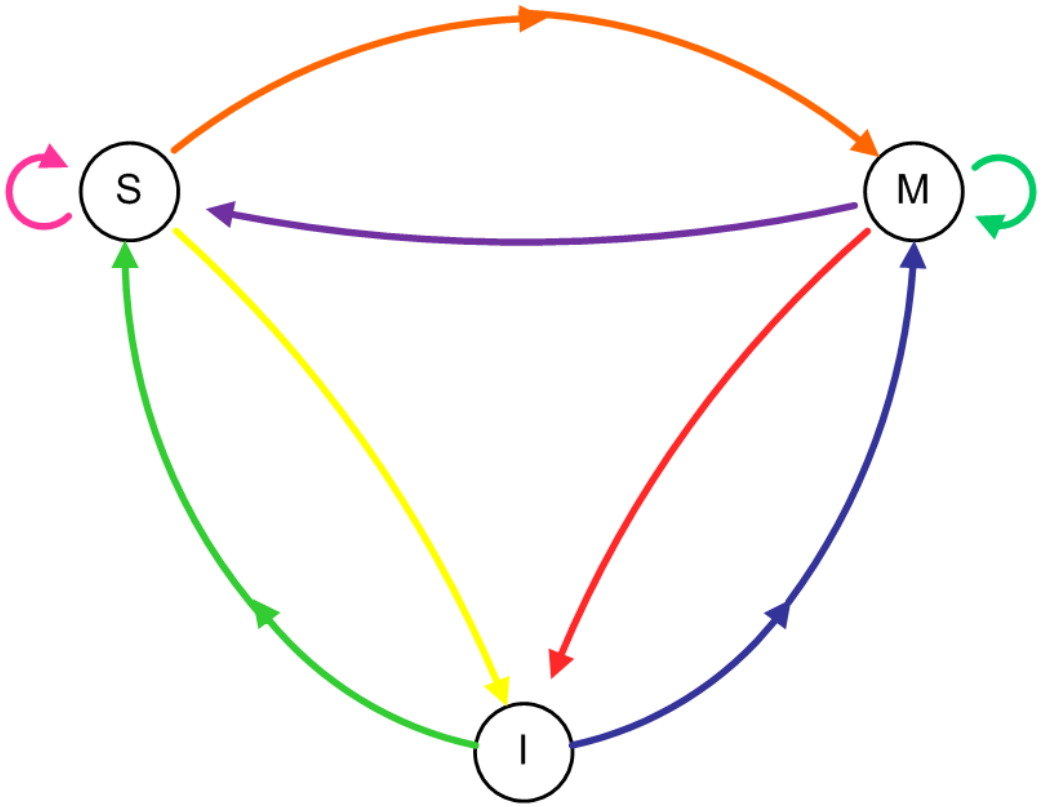
Recall: Cache Coherence

- Definition of coherence
  - Write propagation
    - Write are visible to other processors
  - Write serialization
    - All write to the same location are seen in the same order by all processes



Implementation Challenges

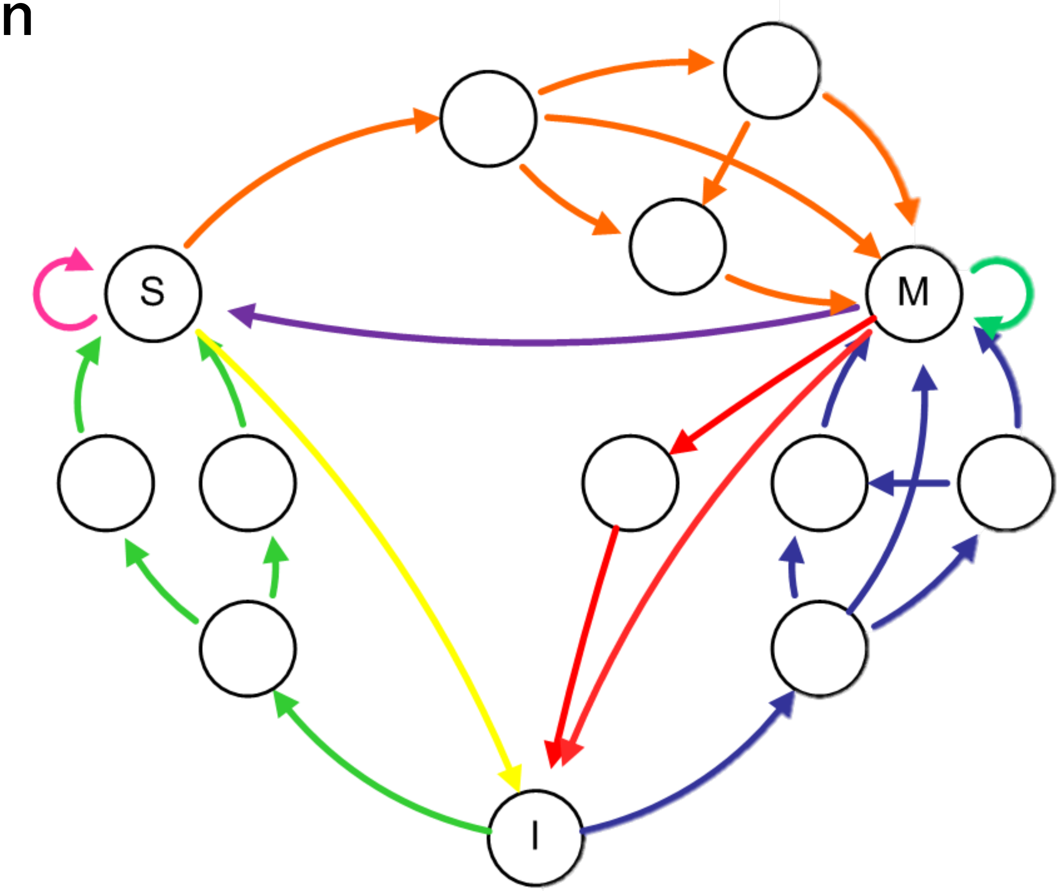
- MSI implementation
  - Stable States



[Vantrease'11]

Implementation Challenges

- MSI implementation
  - Stable States
  - Busy states

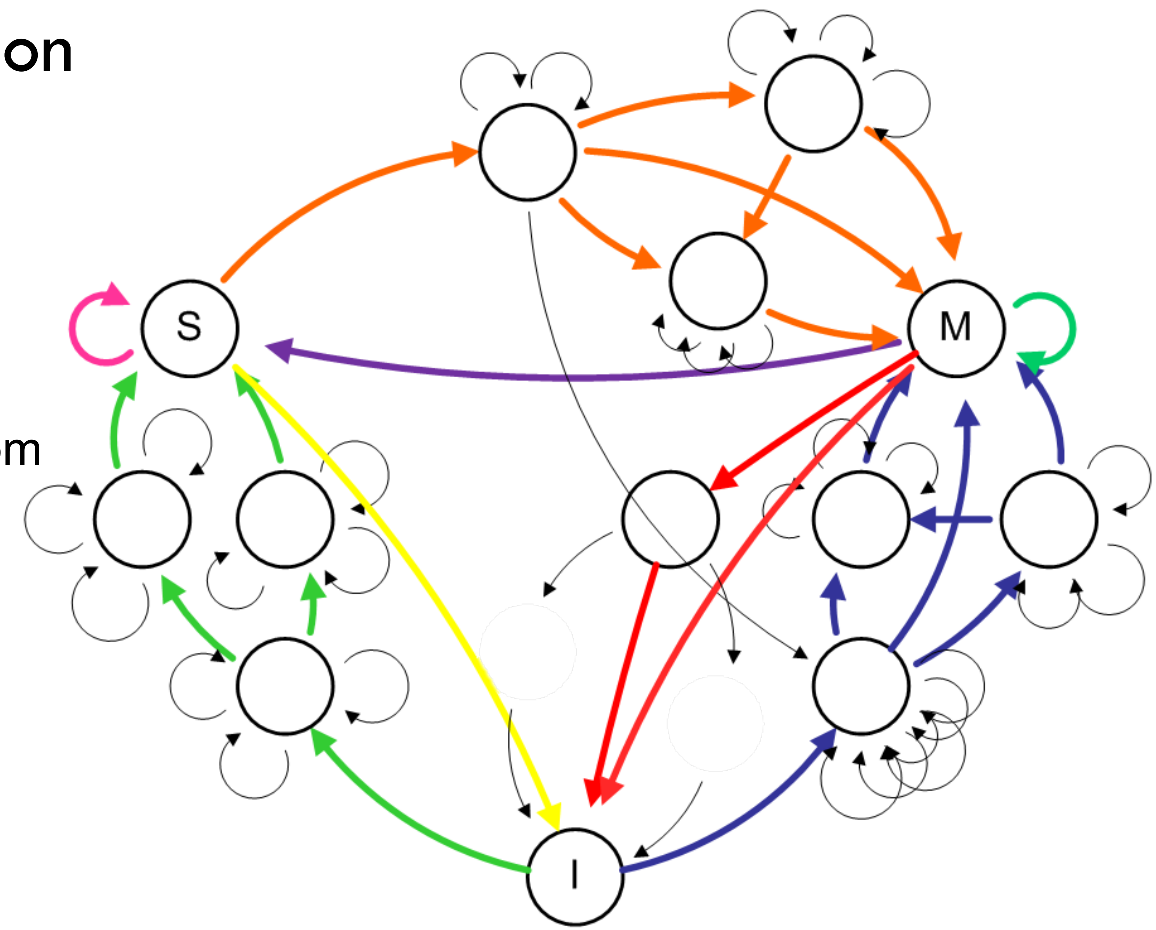


[Vantrease'11]

Implementation Challenges

- MSI implementation
  - Stable States
  - Busy states
  - Races

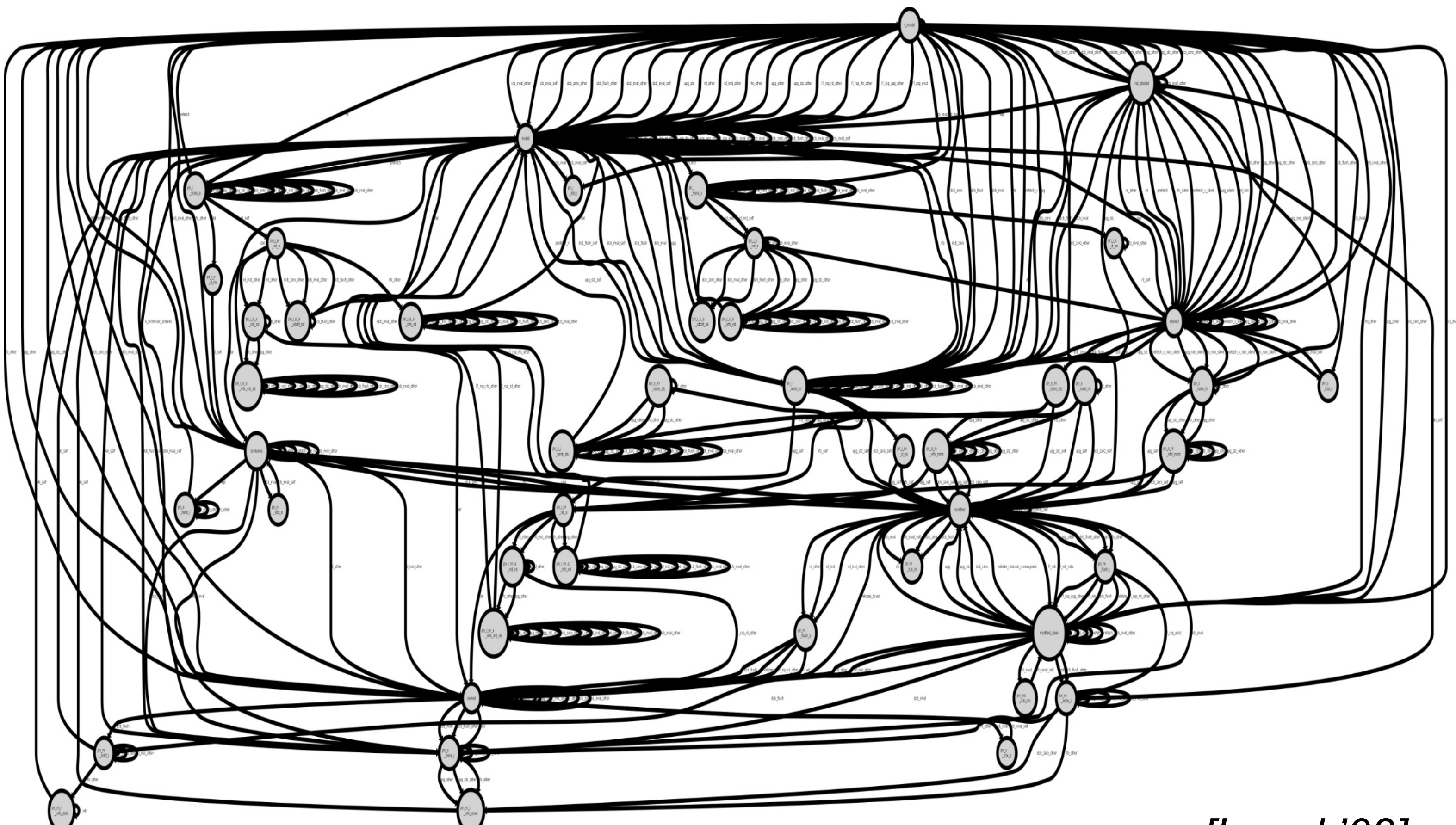
    Unexpected events from concurrent requests to same block



[Vantrease'11]

Cache Coherence Complexity

- A broadcast snooping bus (L2 MOETSI)



[Lepak'03]

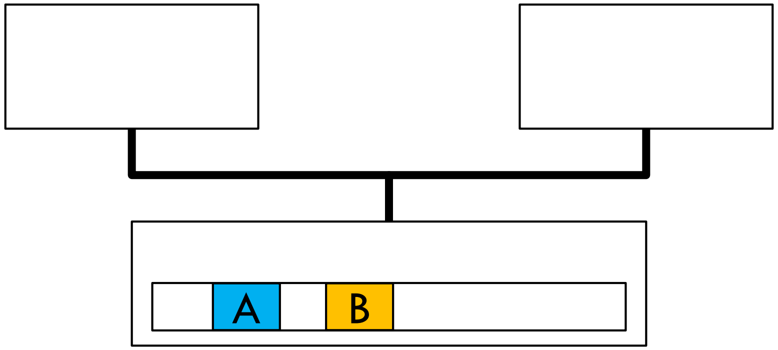
Implementation Tradeoffs

- Reduce unnecessary invalidates and transfers of blocks
  - Optimize the protocol with more states and prediction mechanisms

- Adding more states and optimizations
  - Difficult to design and verify
    - lead to more cases to take care of
    - race conditions
  - Gained benefit may be less than costs (diminishing returns)

Coherence Cache Miss

- Recall: cache miss classification
  - Cold (compulsory): first access to block
  - Capacity: due to limited capacity
  - Conflict: many blocks are mapped to the same set
- New class: misses due to sharing
  - True vs. false sharing



Summary of Snooping Protocols

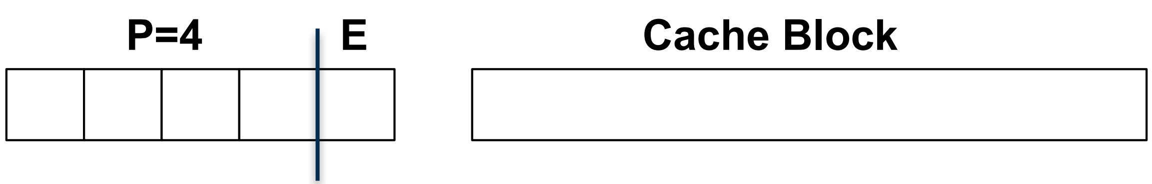
- Advantages
  - Short miss latency
  - Shared bus provides global point of serialization
  - Simple implementation based on buses in uniprocessors
- Disadvantages
  - Must broadcast messages to preserve the order
  - The global point of serialization is not scalable
    - It needs a virtual bus (or a totally-ordered interconnect)

Scalable Coherence Protocols

- Problem: shared interconnect is not scalable
- Solution: make explicit requests for blocks
- Directory-based coherence: every cache block has additional information
  - To track of copies of cached blocks and their states
  - To track ownership for each block
  - To coordinate invalidation appropriately

Directory Information

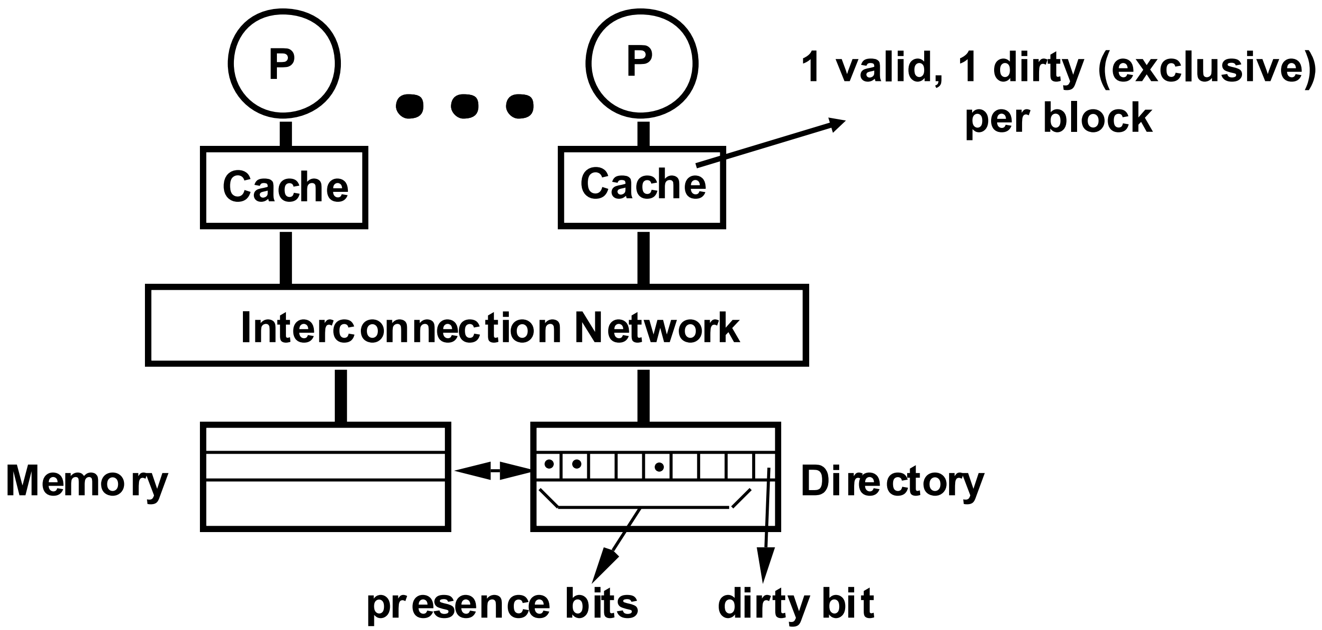
- P+1 additional bits for every cache block
  - One bit used to indicate the block is in each cache
  - One exclusive bit to indicate the cache has the only copy (can update without notifying others)
- On a read, set the cache's bit and arrange the supply of data
- On a write, invalidate all caches that have the block and reset their bits



How to organize directory information?

Directory Organization

- Example: central directory for P processors
  - For each cache block in memory
    - p presence bits, 1 dirty bit
  - For each cache block in cache
    - 1 valid bit, and 1 dirty (owner) bit



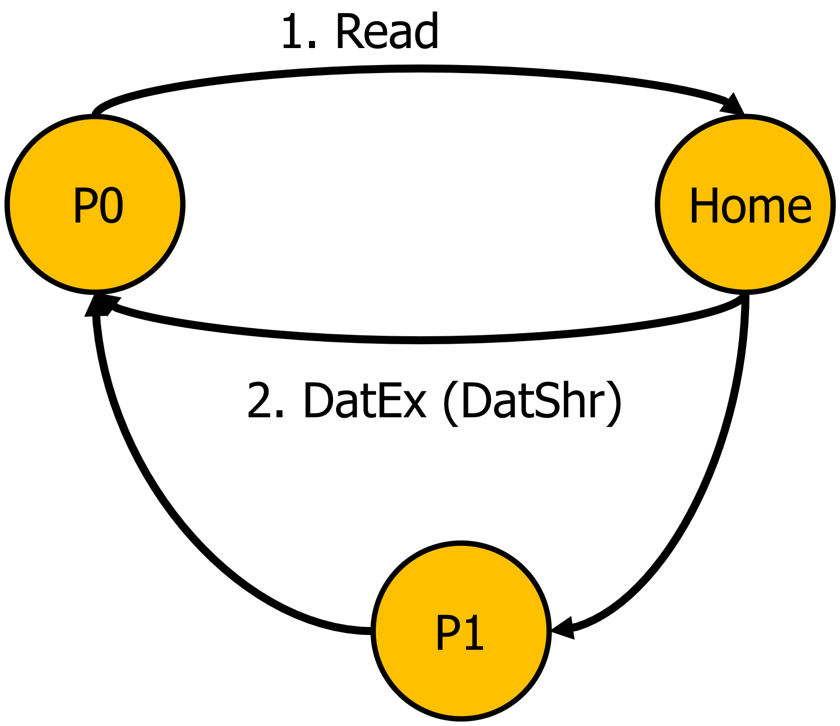
Directory Protocol

- Three states (similar to snoopy protocol)
  - Shared: more than one processors have data, memory up-to-date
  - Uncached: no processor has it; not valid in any cache
  - Exclusive: one processor has data; memory out-of-date

- Basic terminology
  - Local node, where a request originates
  - Home node, where the memory location of an address resides
  - Remote node, has copy of a cache block, whether exclusive or shared

Read Request

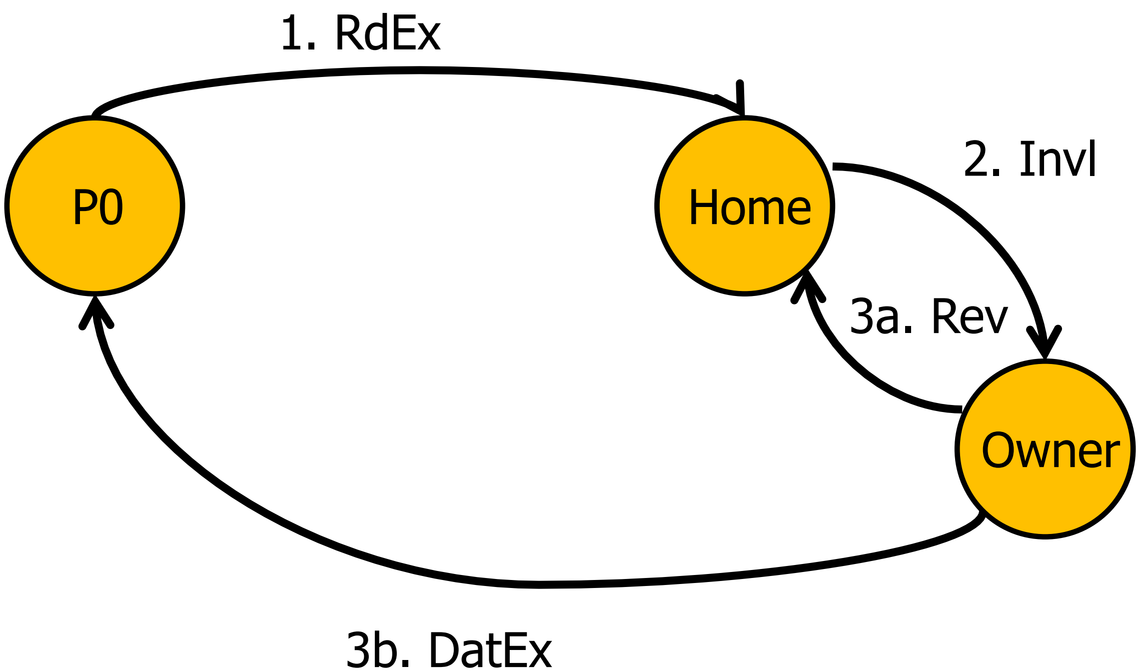
- P0 reads a cache location



[Culler/Singh]

ReadEx Request

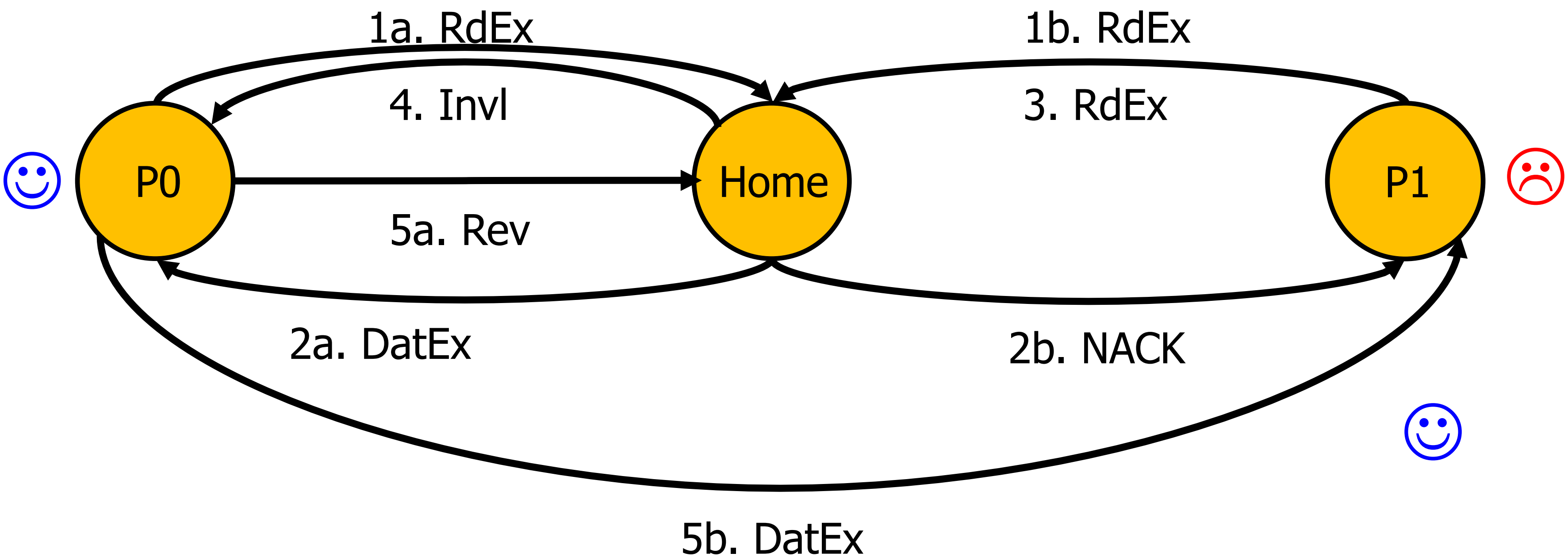
- Avoid roundtrip to home by sending data directly from owner



[Culler/Singh]

Write Contention

- NACKing mechanism



What are the challenges?

[Culler/Singh]

Design Challenges

- Fairness: which requester is preferred on a conflict?
  - Consider distance and delivery order of interconnect

- Race condition: how to keep the proper sequence
  - NACK requests to busy blocks (pending invalidate)
    - Original requestor retries
  - Queuing requests and granting in sequence

Summary of Directory Protocols

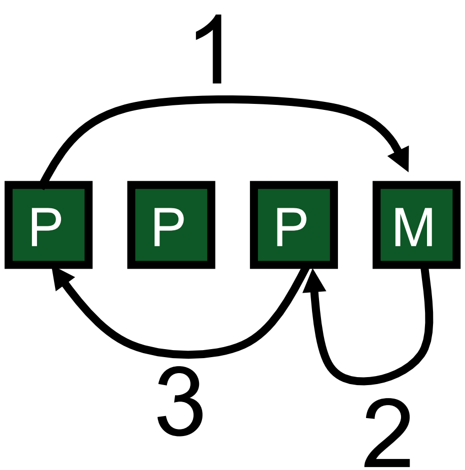
- Advantages
  - Does not require broadcast to all caches
  - Exactly as scalable as interconnect and directory storage (much more scalable than bus)

- Disadvantages
  - Adds indirection to miss latency (critical path)
    - request → directory → memory
  - Requires extra storage space to track directory states
  - Protocols and race conditions are more complex

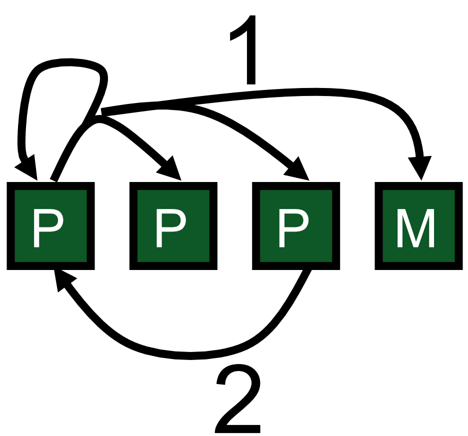
Avoid Indirection

- Can we get the best of both snooping and directory protocols?
  - Direct cache-to-cache misses (broadcast is ok)
  - What if unordered interconnect (e.g., mesh) was used?

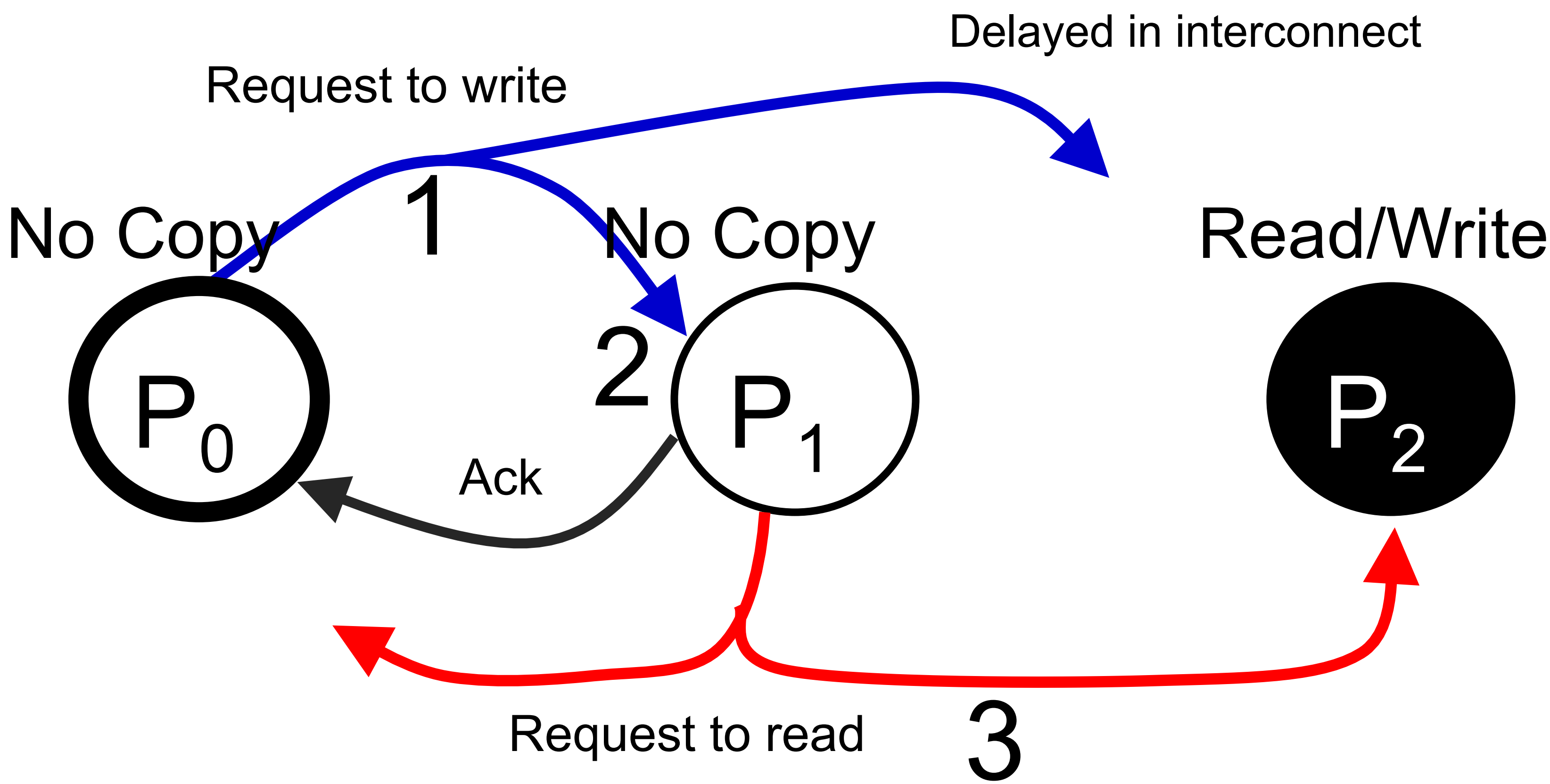
Directory Protocol



Hybrid Protocol

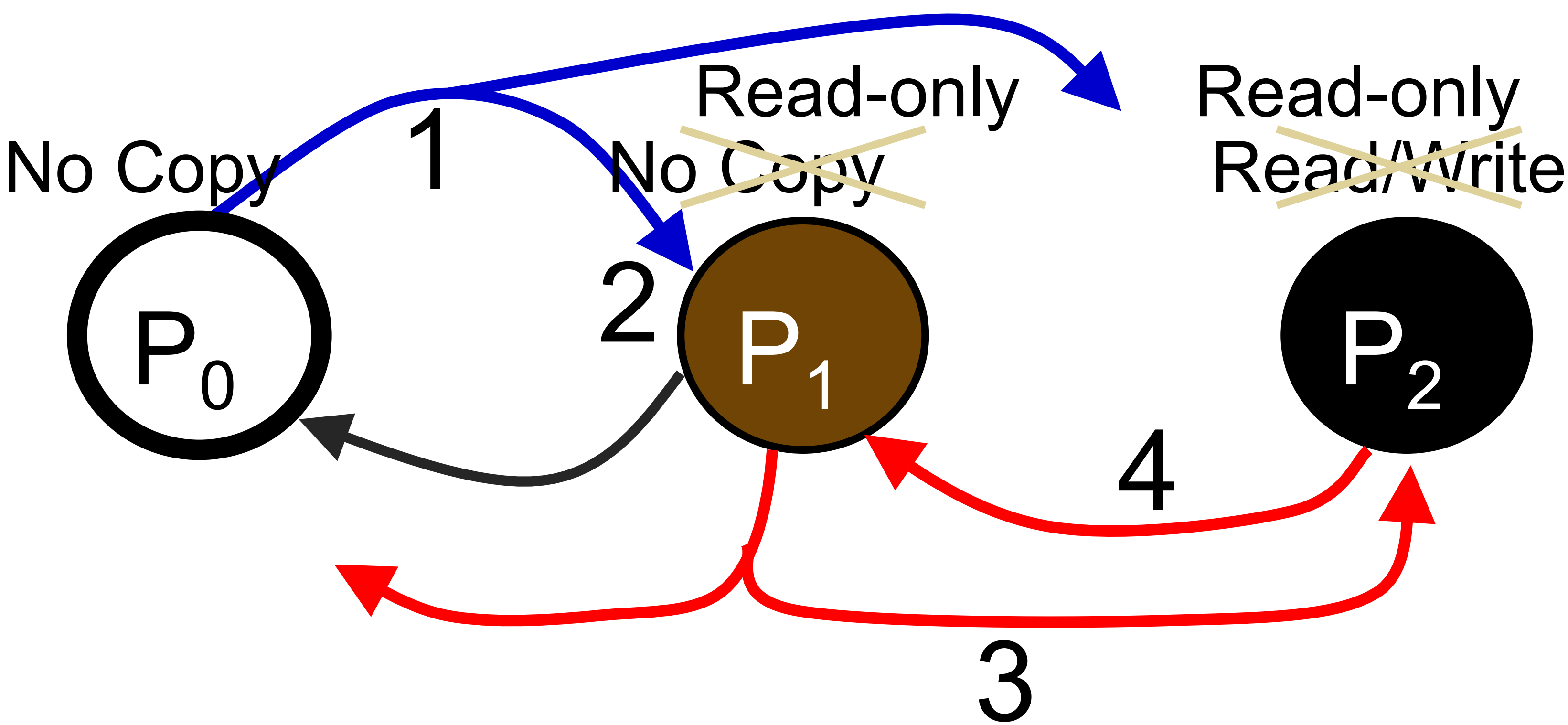


An Example Problem



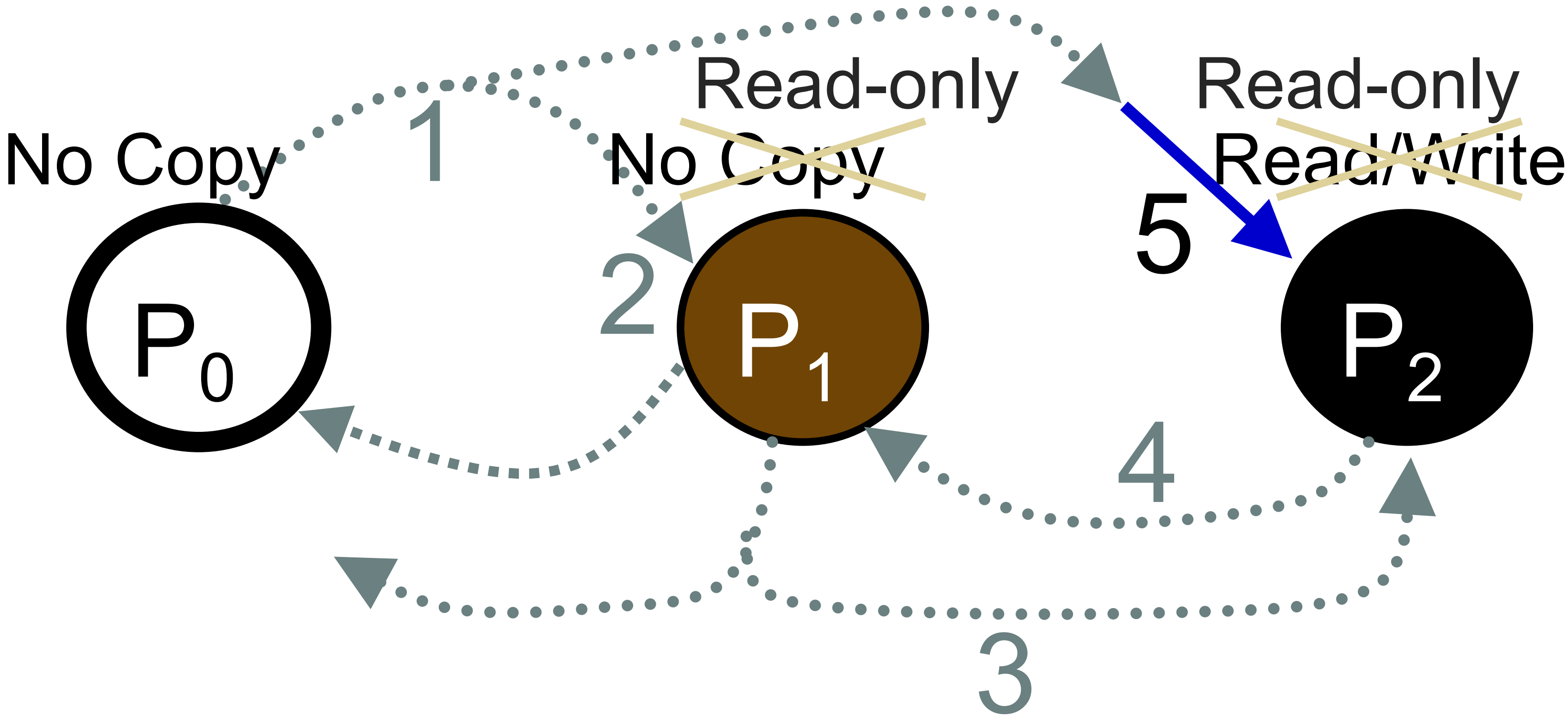
- P_0 issues a request to write (delayed to P_2)
- P_1 issues a request to read

An Example Problem



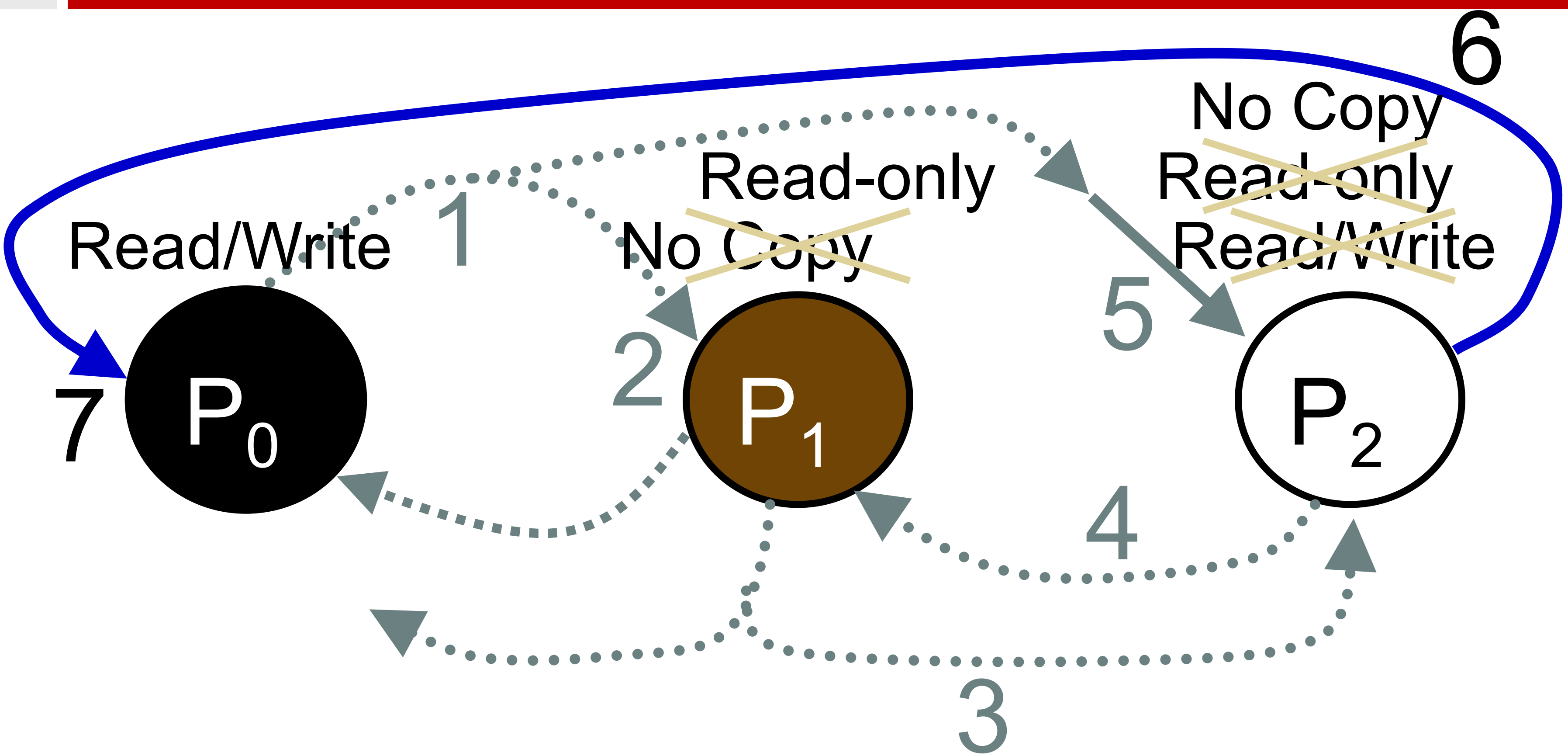
- P_2 responds with data to P_1

An Example Problem



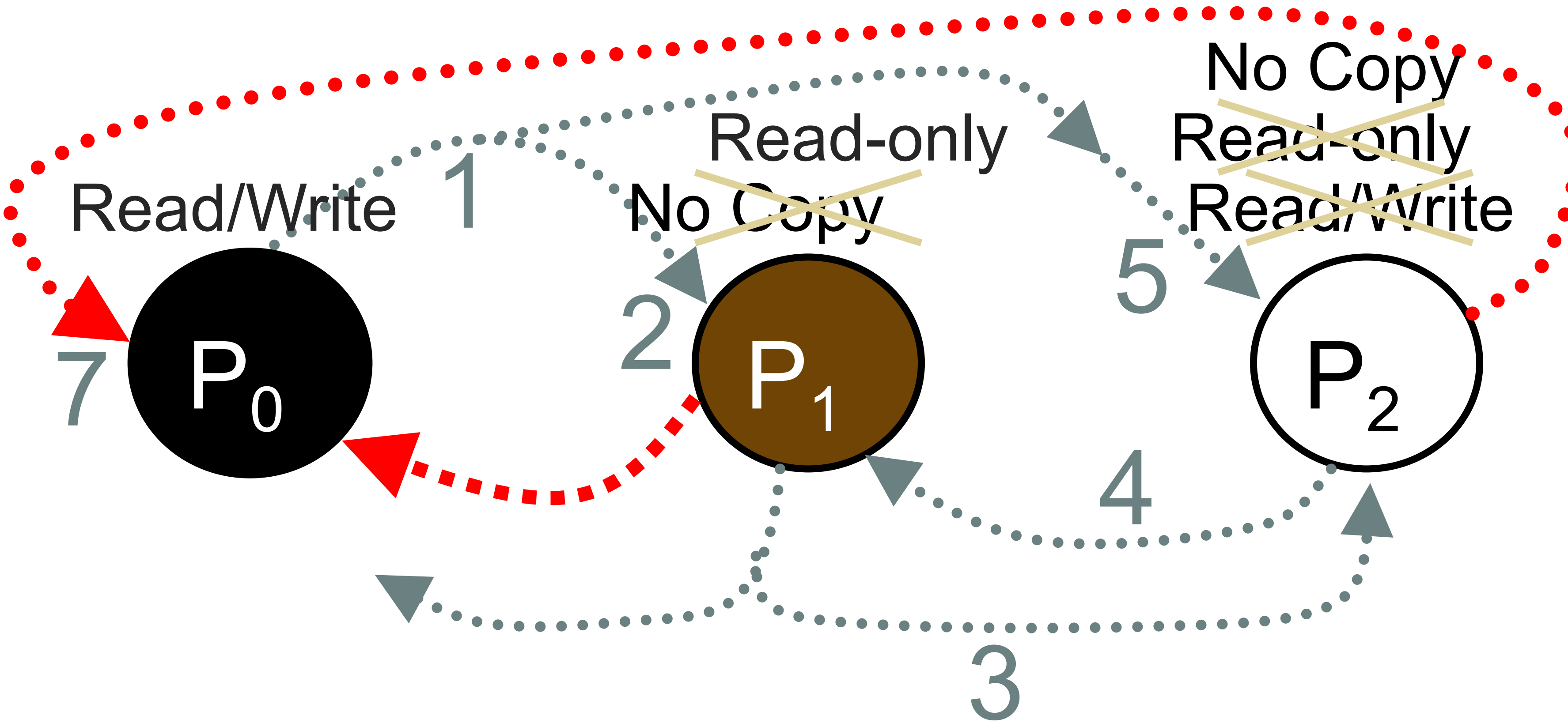
- P_0's delayed request arrives at P_2

An Example Problem



• P_2 responds to P_0

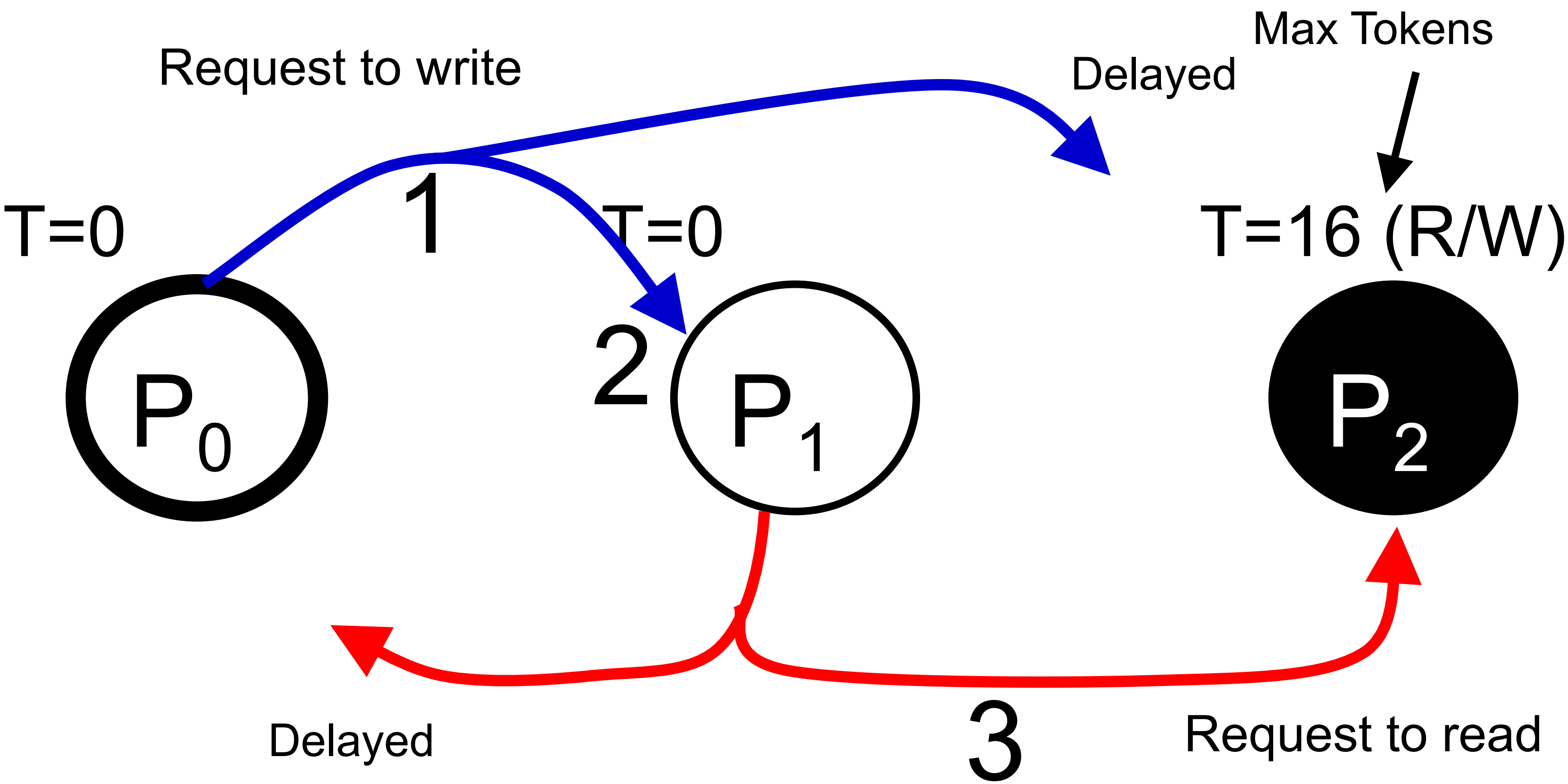
An Example Problem



Problem: P_0 and P_1 are in inconsistent states

Locally "correct" operation, globally inconsistent

Token Coherence



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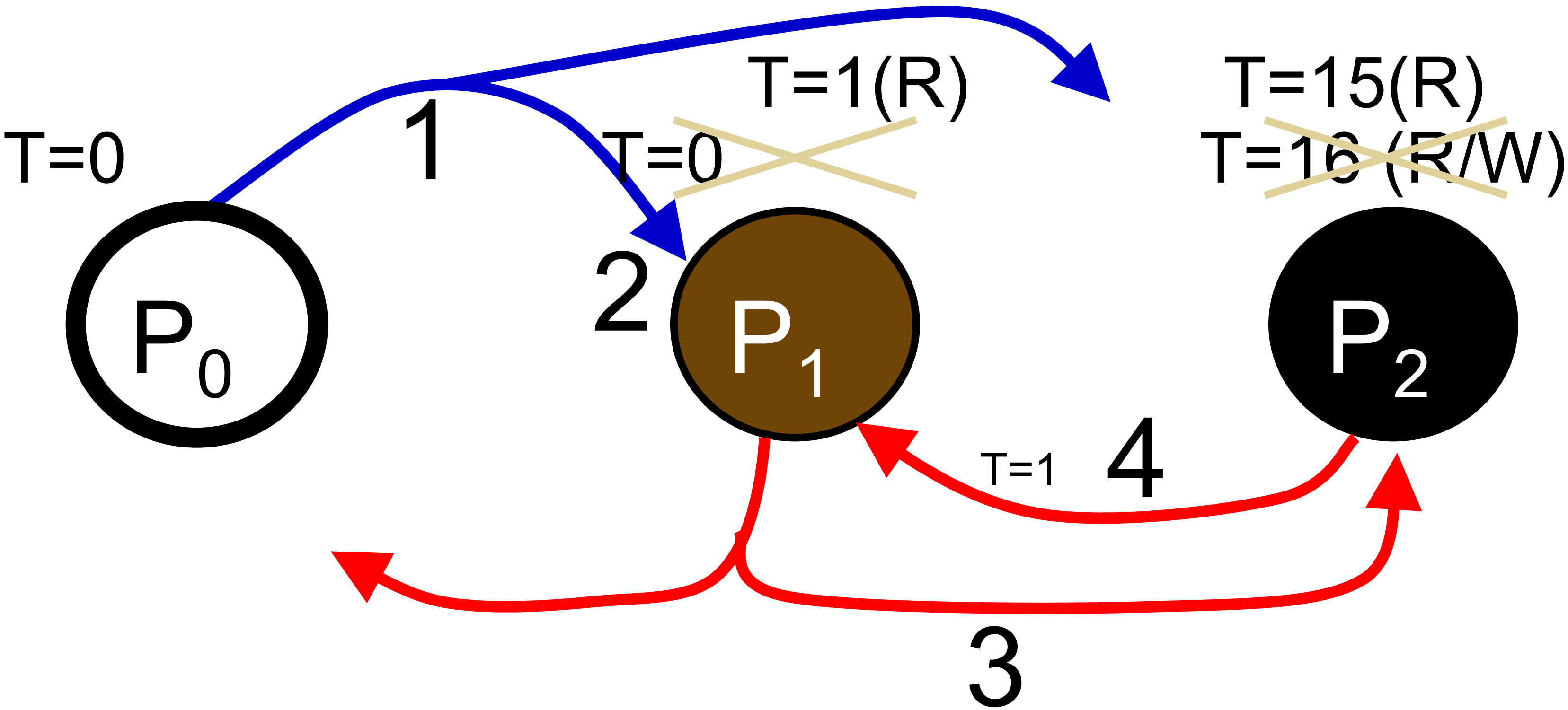
- P_1 issues a request to read

[Martin'03]

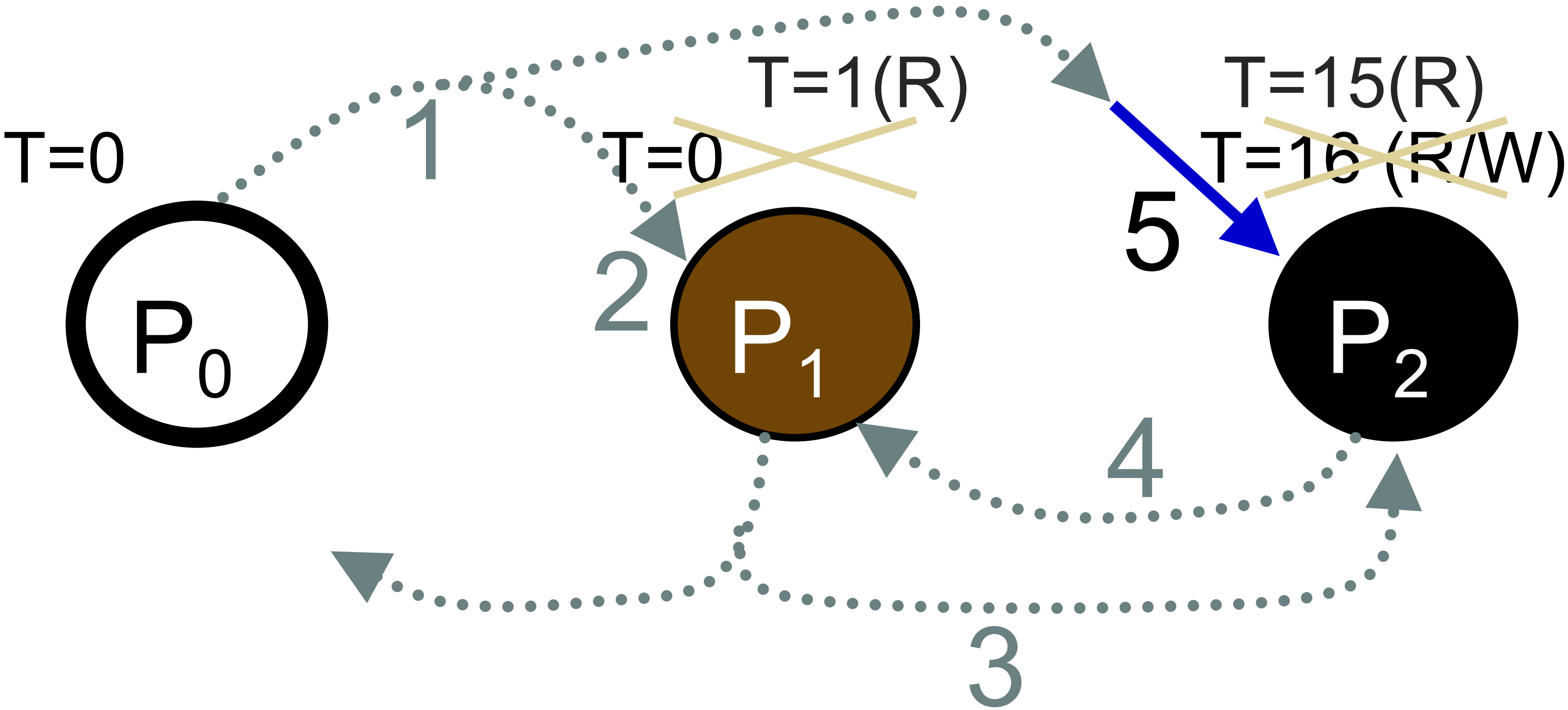
Token Coherence



• P_2 responds with data to P_1

[Martin'03]

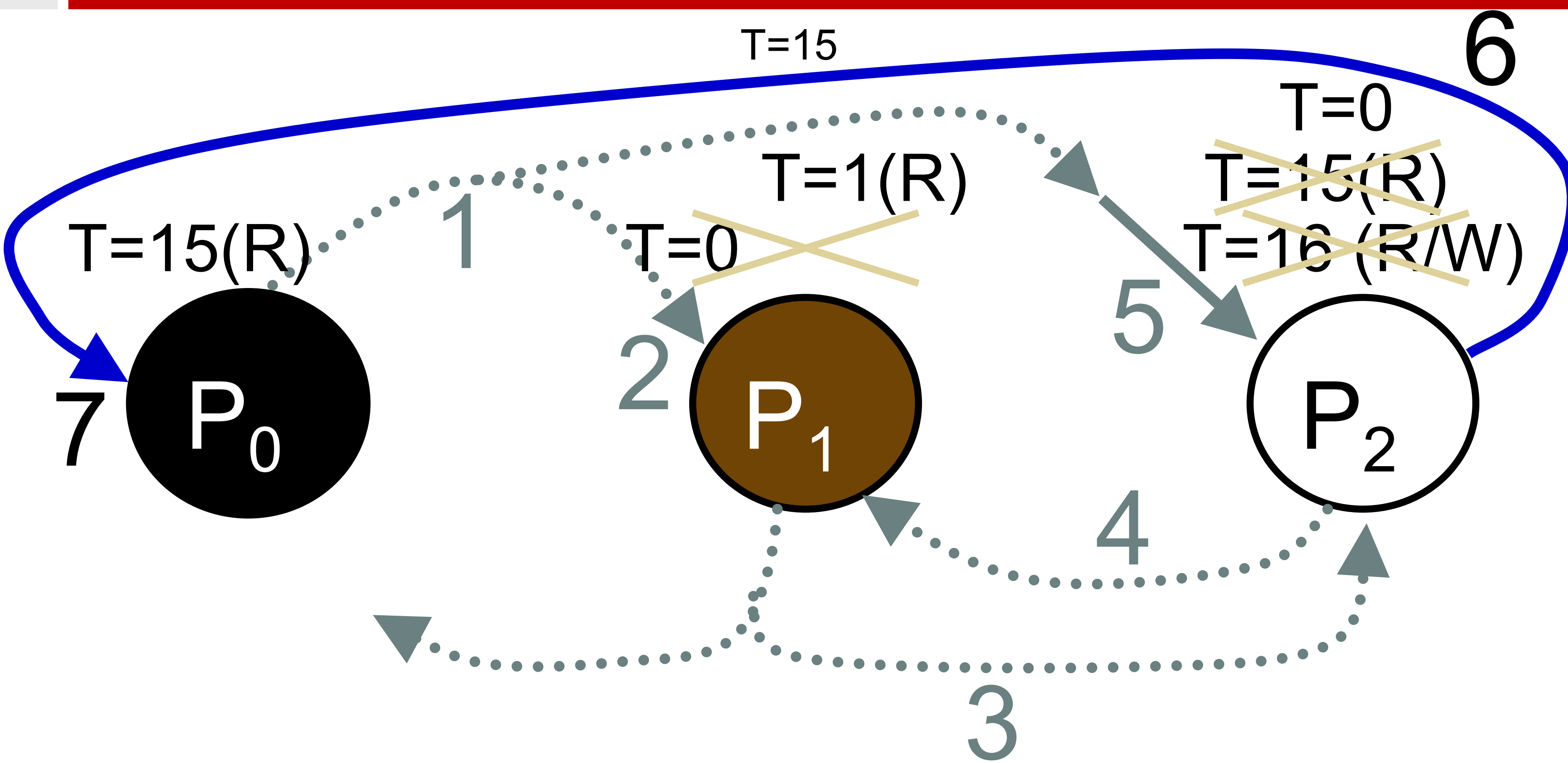
Token Coherence



- P_0's delayed request arrives at P_2

[Martin'03]

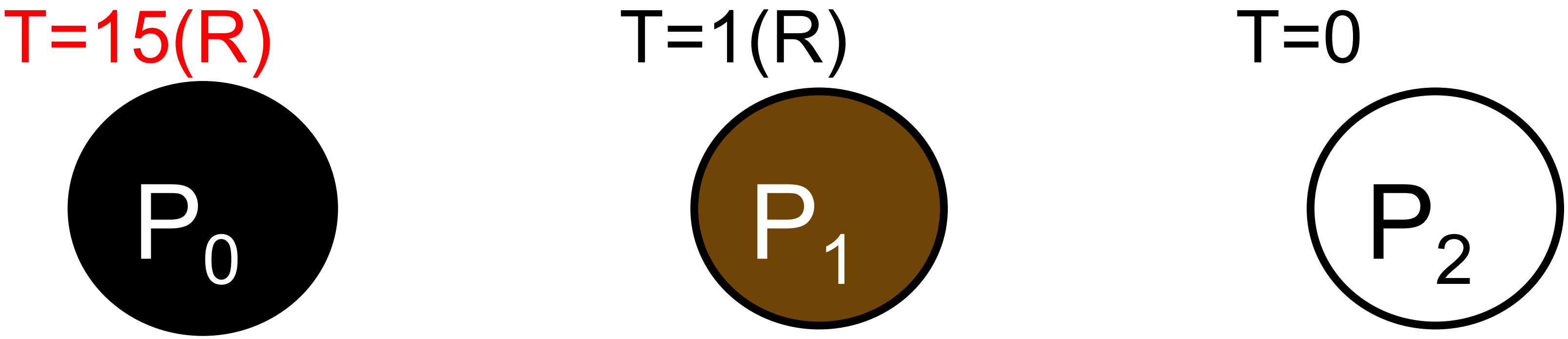
Token Coherence



- P_2 responds to P_0

[Martin'03]

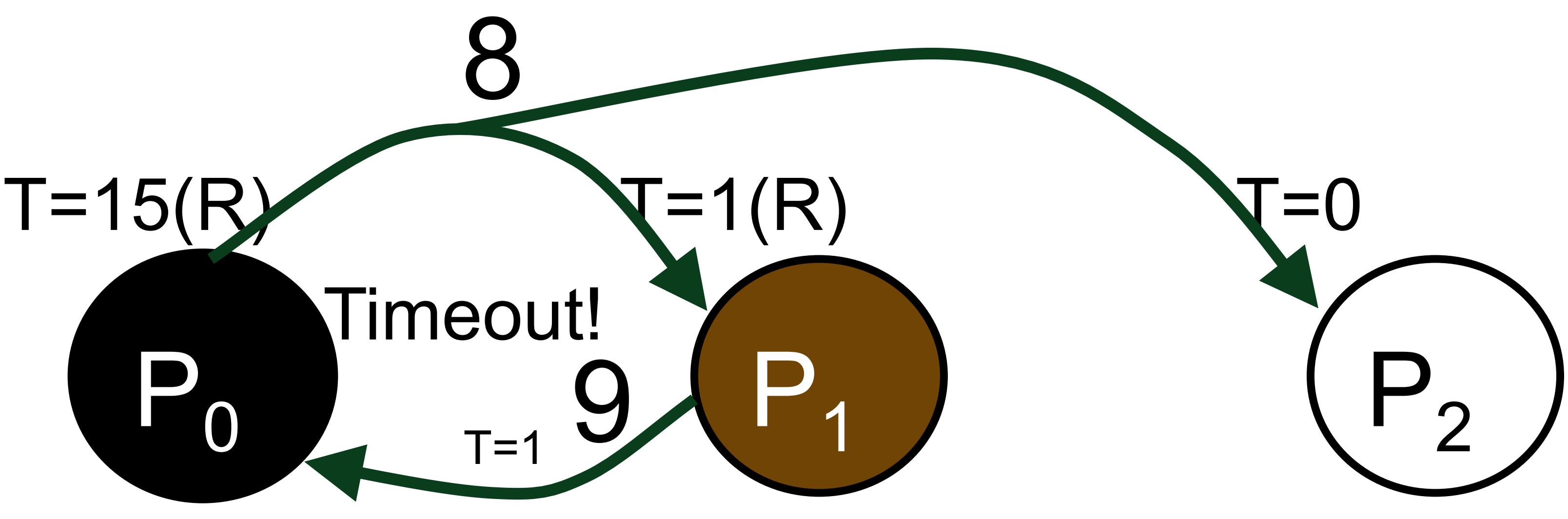
Token Coherence



Now what? (P_0 wants all tokens)

[Martin'03]

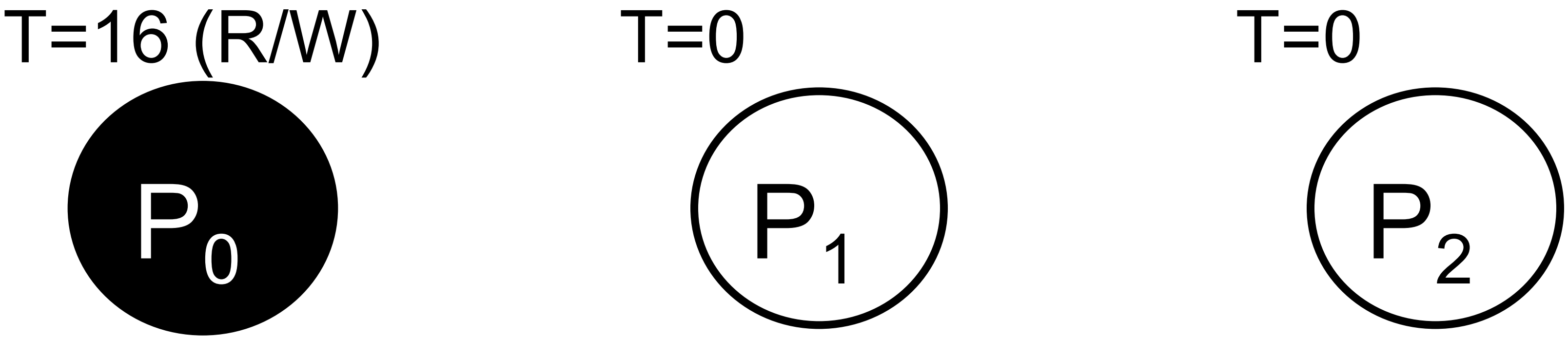
Token Coherence



- P_0 reissues request
- P_1 responds with a token

[Martin'03]

Token Coherence



One final issue: What about starvation?

•P_0's request completed

[Martin'03]