Efficient Object-Based Software Transactions

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Transactions: Philosophy

- **Transactions will be large & small, short & long**
  - **Mechanisms should be *unbounded***
- **They will be frequent and visible in user code**
  - **Easy to use**
  - **Not hidden in libraries**
- **Implemented with general-purpose mechanisms**
  - **In addition to synchronization, useful for fault tolerance, exception handling, backtracking, priority scheduling...**
- ***Object-based* transactions**
  - **Expose a richer abstraction**
  - **Move beyond emulating an unavailable HTM**

Why object-based transactions?

- **Synchronization abstraction matches programming abstraction**
  - **No false sharing due to variables incidentally colocated in same word/cache line/page. Possible deadlock!**
- **Matching the programming abstraction allows better compiler analysis and optimization of transactional code**
  - **For example, escape analysis**
- **Performance benefits for long-running transactions**
  - **Pay cloning costs up-front, then run at full-speed in own copy of the object graph**

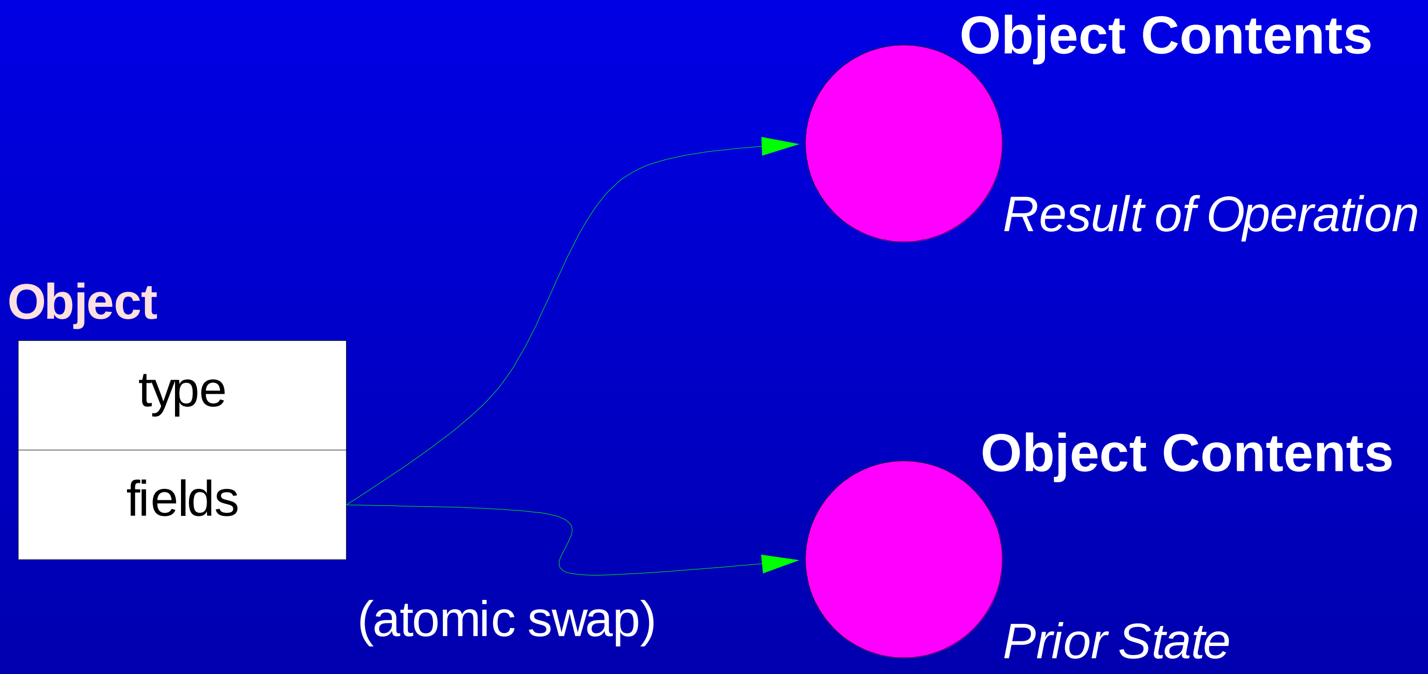
Three Big Ideas

- **Functional Arrays: A solution to the Large Object Problem**
- **Cooperating with FLAGs**
  - **Non-transactional code interacting with transactions**
  - **Software transactions interacting with a Hardware Transactional Memory**
- **Model-checking Software Transactions**

The Large Object Problem

Single-Object Protocol

Valid for operations on a single object only.



- **Object representation contains a pointer to object contents.**
- **Object mutation inside transaction creates new object contents.**

Single-Object Protocol

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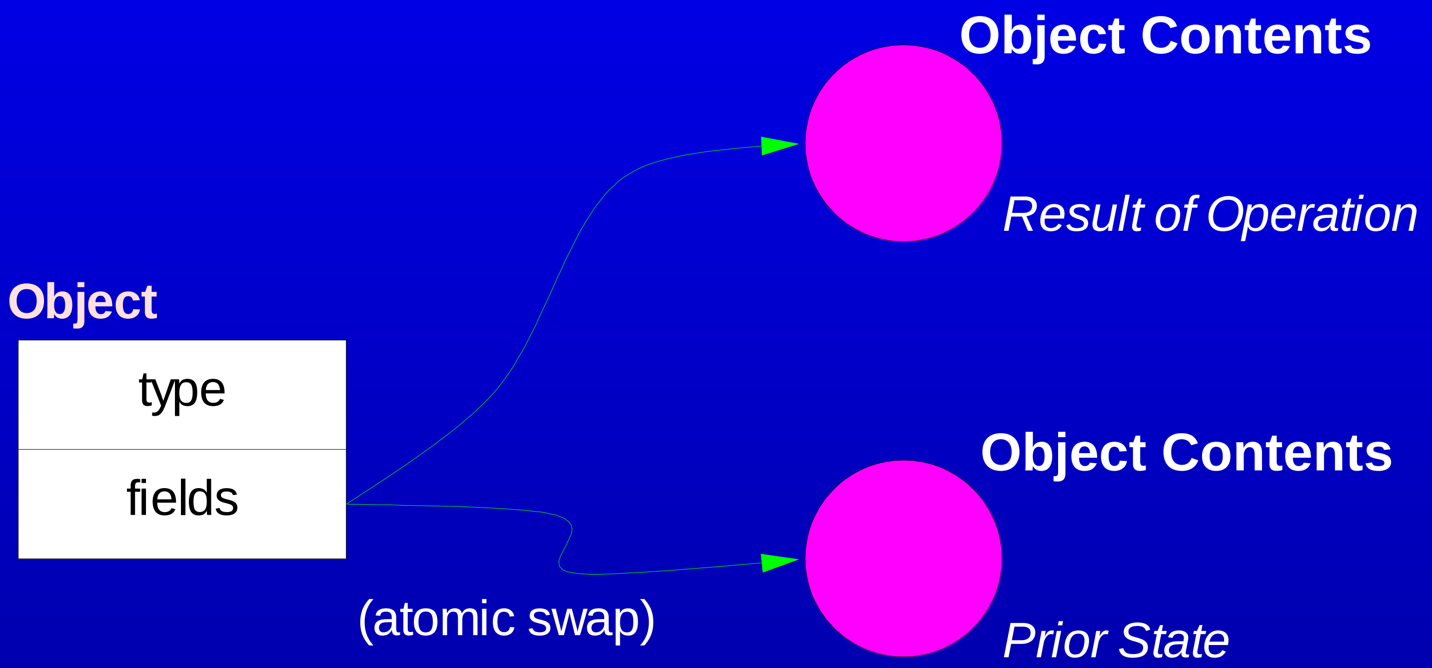
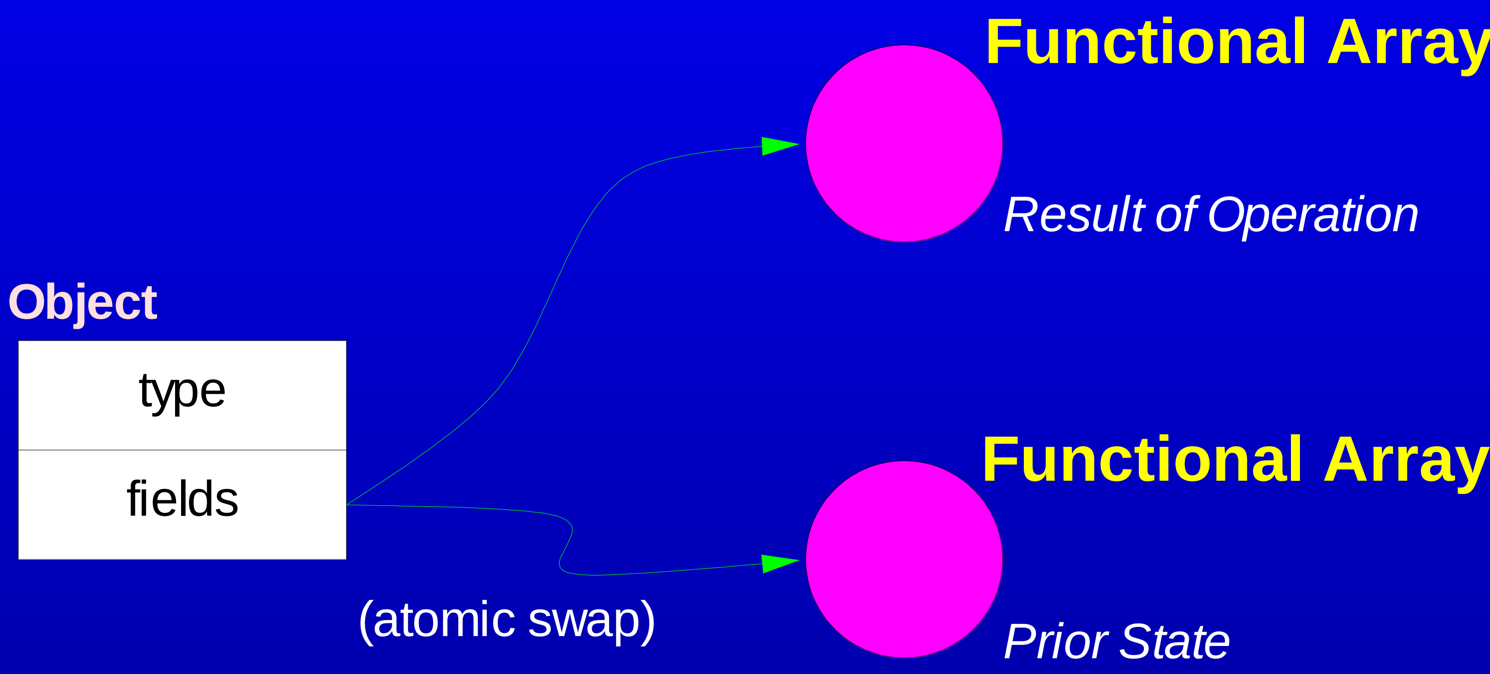


- **At start of transaction, load and remember `fields` pointer as *prior state*.**
- **To commit, compare-and-swap the *result of operation* for *prior state*.**

Single-Object Protocol

Valid for operations on a single object only.



- **Large Object Problem: cloning *prior state* for *result of operation* is O(object size)**
- **Solution: use a data structure where cloning is cheap – O(1) would be nice!**

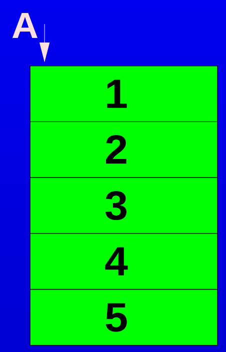
Functional arrays

- Functional arrays are **persistent**: after an element is updated both the new and the old contents of the array are available for use.
- Fundamental operation:

$$\mathrm{Update}(A, i, v) : A \to N_0 \to V \to A$$

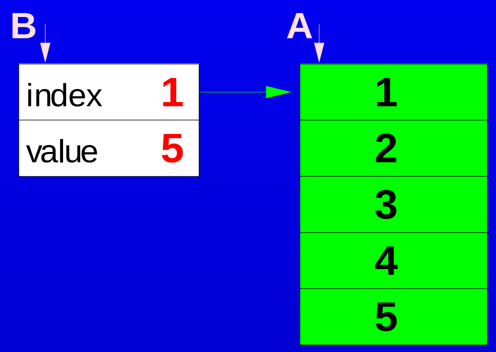
- Arrays are just mappings from integer to value; any persistent map can be used as a functional array.
- A *fast* functional array will have **O(1) access and update** for the common cases.
  - Variant of shallow binding due to [Chuang '94]

Functional Arrays using Shallow Binding



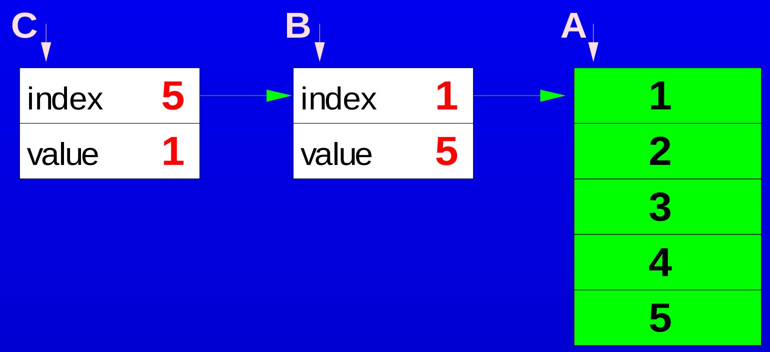
- **A functional array is either a *cache node*...**

Functional Arrays using Shallow Binding



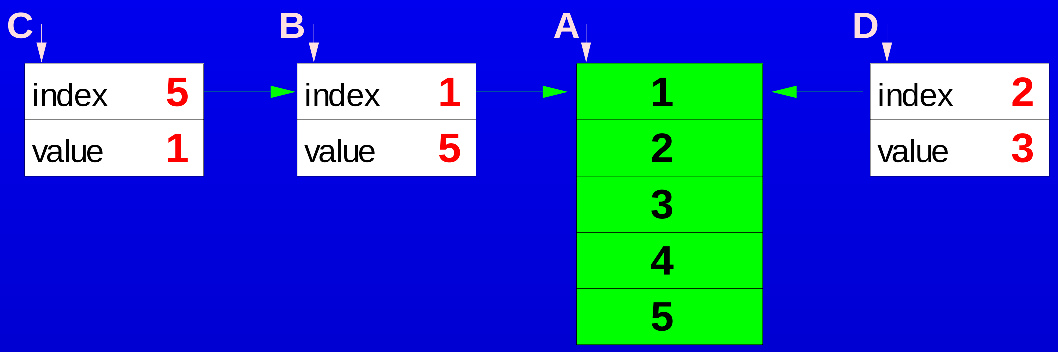
- A functional array is either a ***cache node*** or a ***difference node***.
- A[1]=1 but B[1]=5

Functional Arrays using Shallow Binding



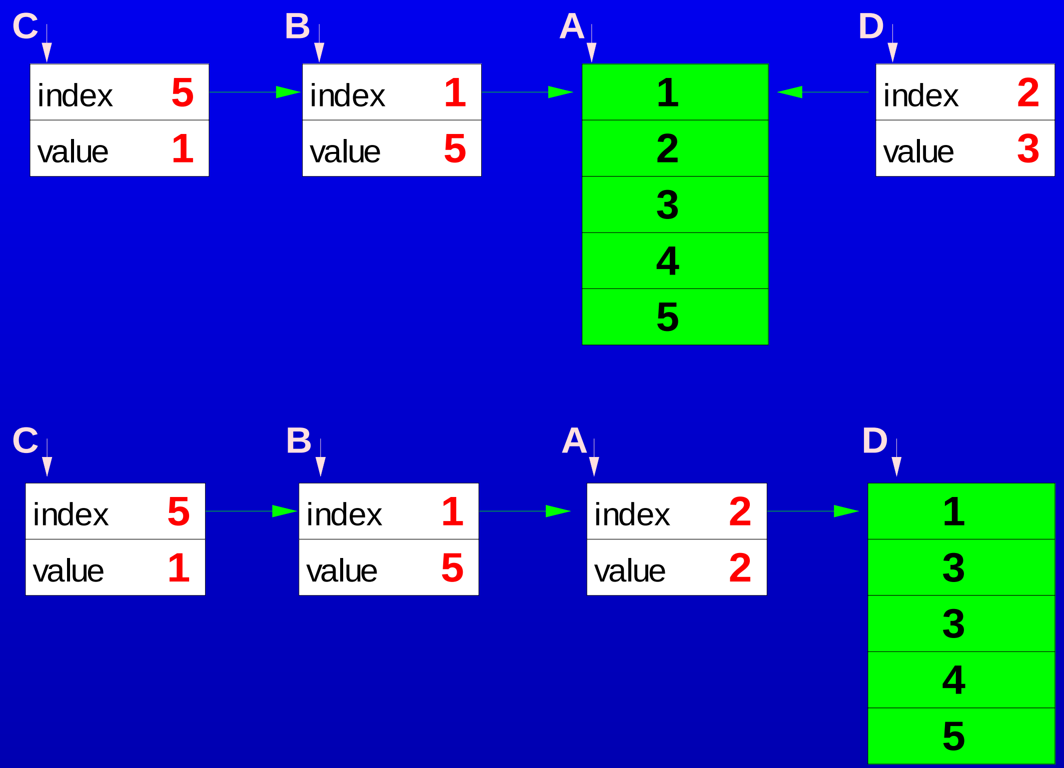
- **Changing one element is O(1)**

Functional Arrays using Shallow Binding



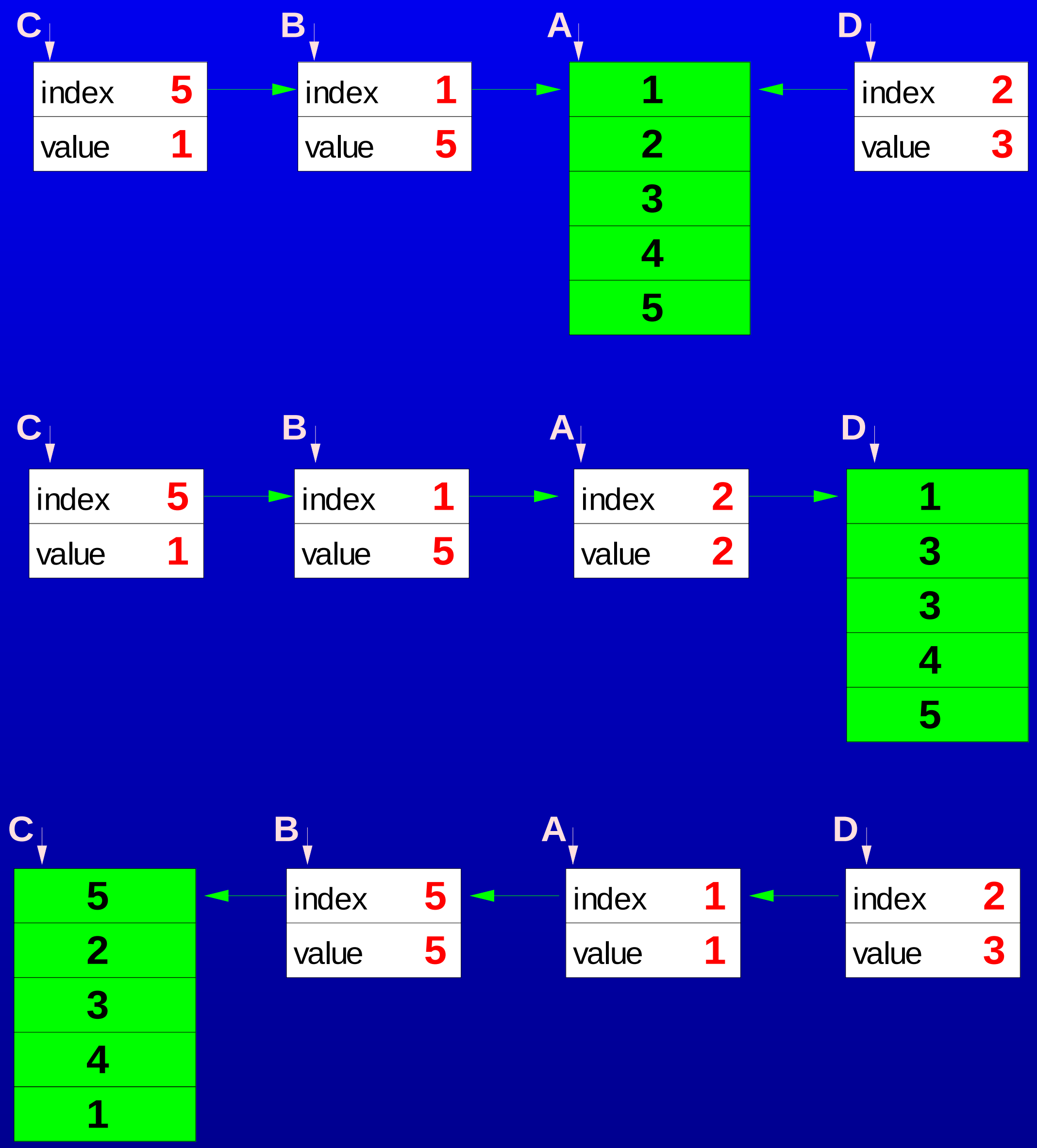
- A[1] = D[1] = 1 C[1] = B[1] = 5
- C[5] = 1 D[2] = 3

Functional Arrays using Shallow Binding



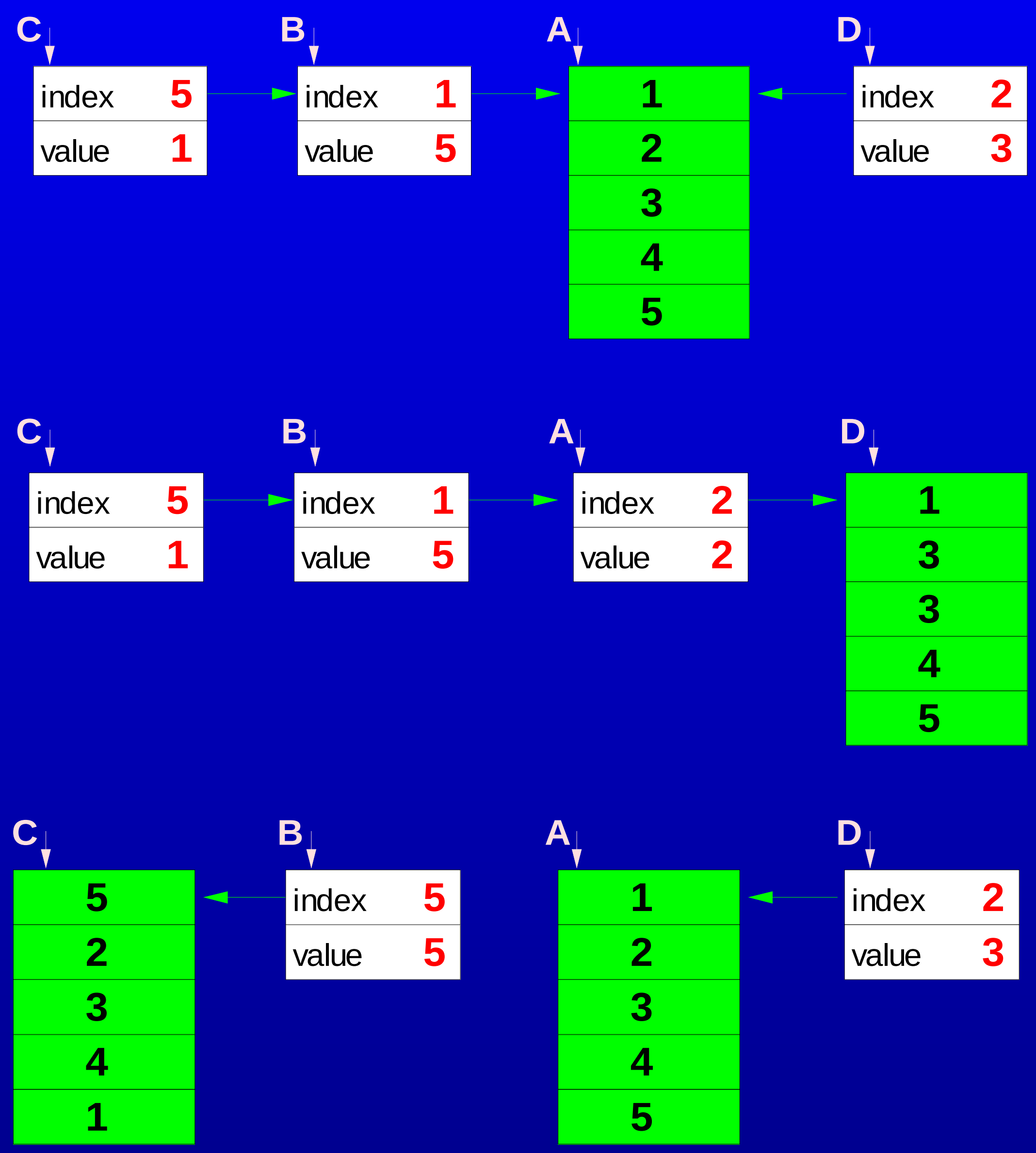
- **We *rotate* the cache node on reads to keep access times fast.**
- **The bottom shows the graph after D is read.**

Functional Arrays using Shallow Binding



- **C is read.**
- **Ping-pong danger!**

Functional Arrays using Shallow Binding



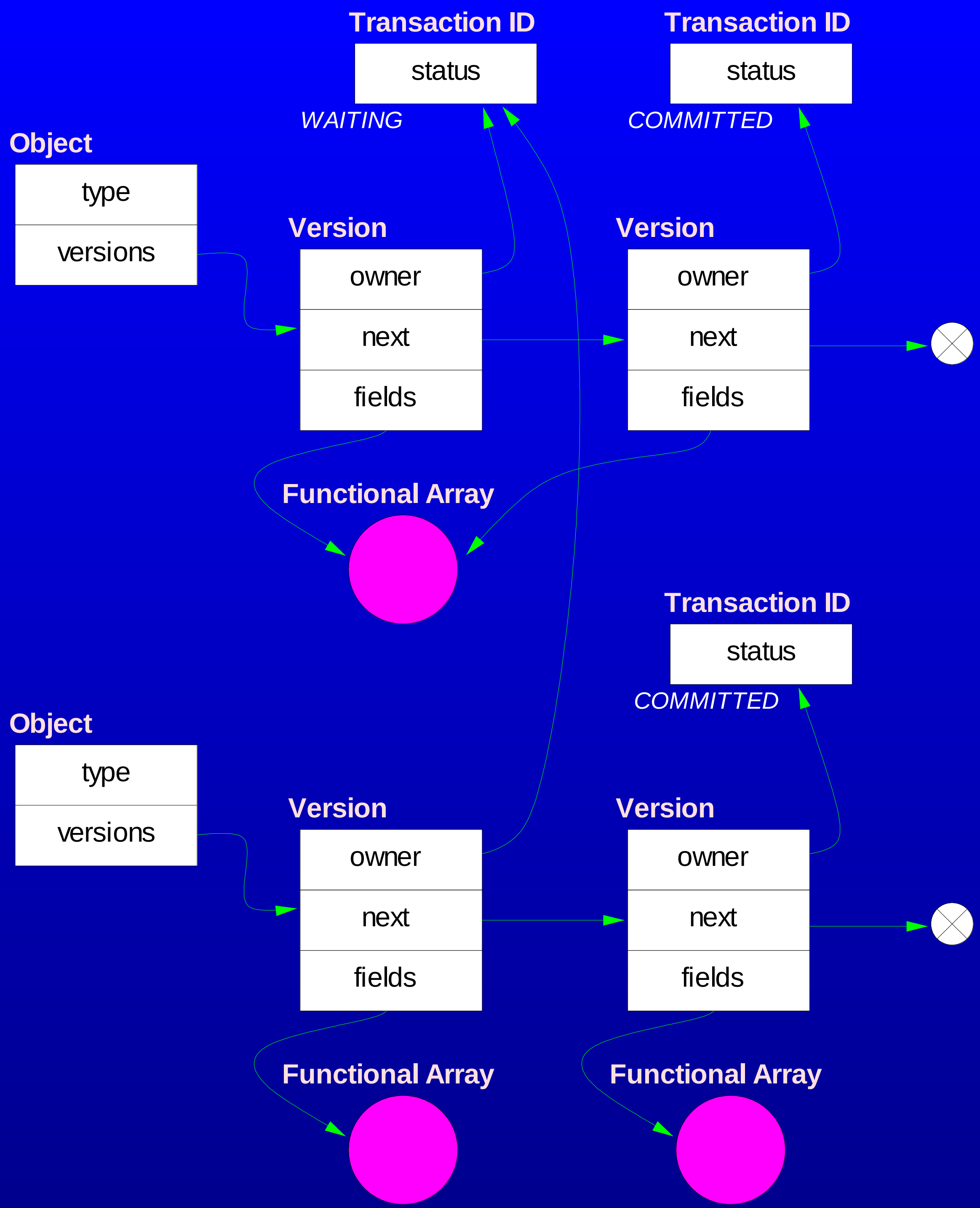
- ***Split*** **with 1/*N* chance.**

Making a non-blocking algorithm

- **Adding difference nodes is easy.**
- **Two hard operations:**
  - **Rotation**
  - **Splitting**
- **These can be made non-blocking [Ananian '03]**
- **Can also use a small Hardware Transactional Memory to implement these operations.**

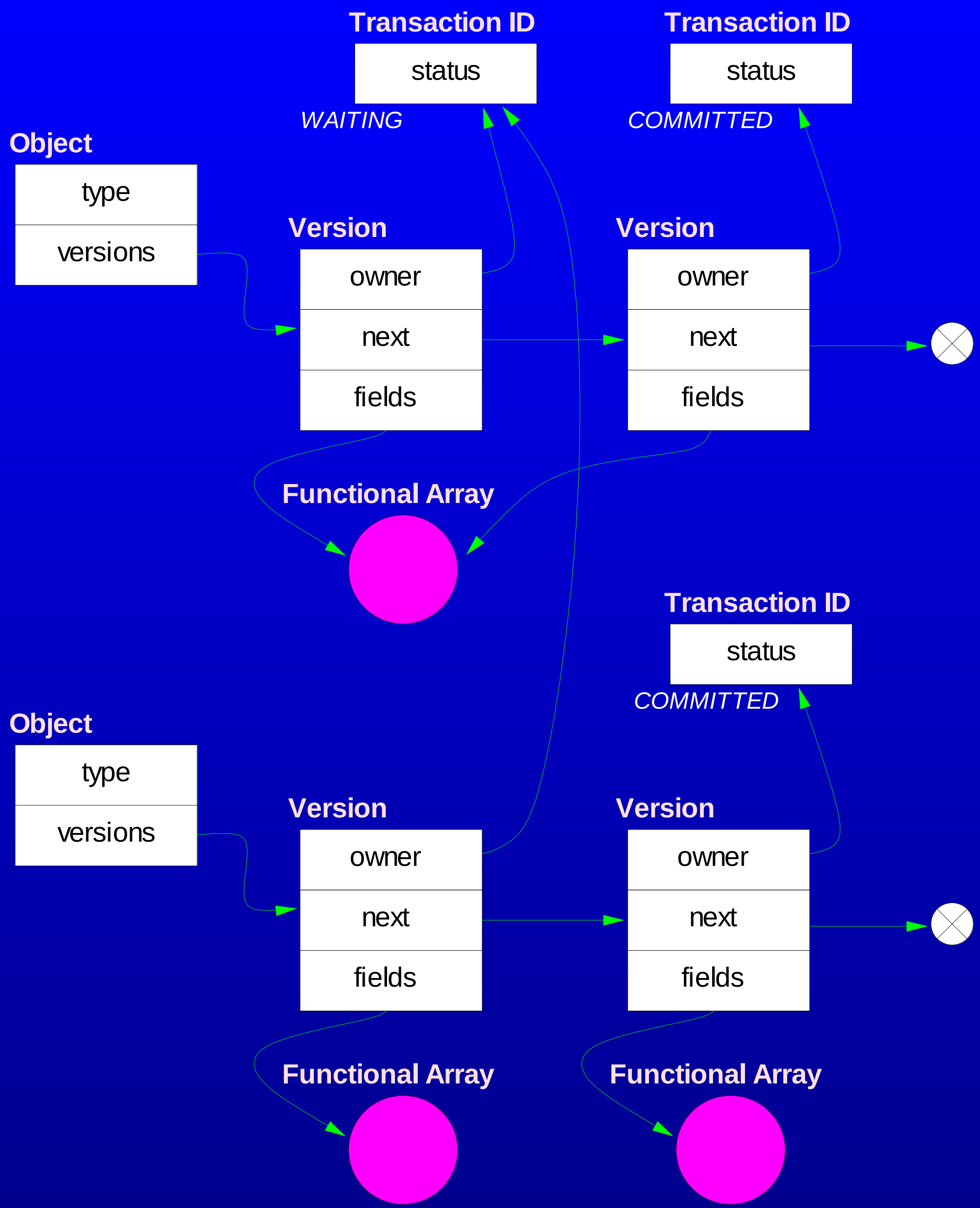
Multiple-Object Protocol

- **Objects point to lists of versions.**
- **Each version has an associated Transaction ID and field array reference.**
- **Transaction IDs are initialized to WAITING and are changed exactly once to COMMITTED or ABORTED.**



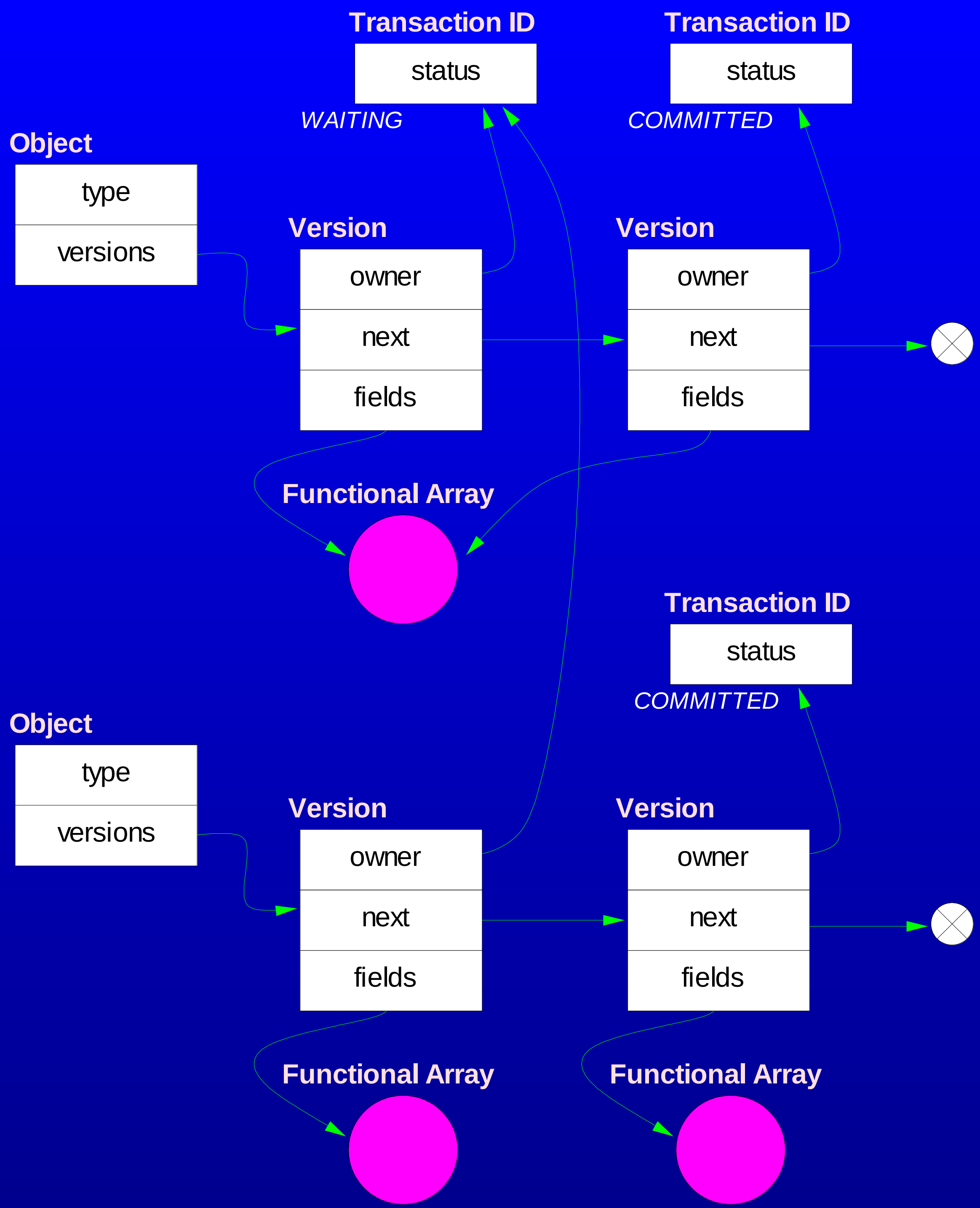
Multiple-Object Protocol

- **At end of transaction, attempt to set Transaction ID to COMMITTED.**
- **Value of object is the value of the first committed version.**
- **ABORTED versions can be collected.**



Multiple-Object Protocol

- **Only one WAITING version allowed on versions list, and it must be at the head.**
- **Before we can link a new version onto the versions list, we must ensure that every other version is either COMMITTED or ABORTED.**



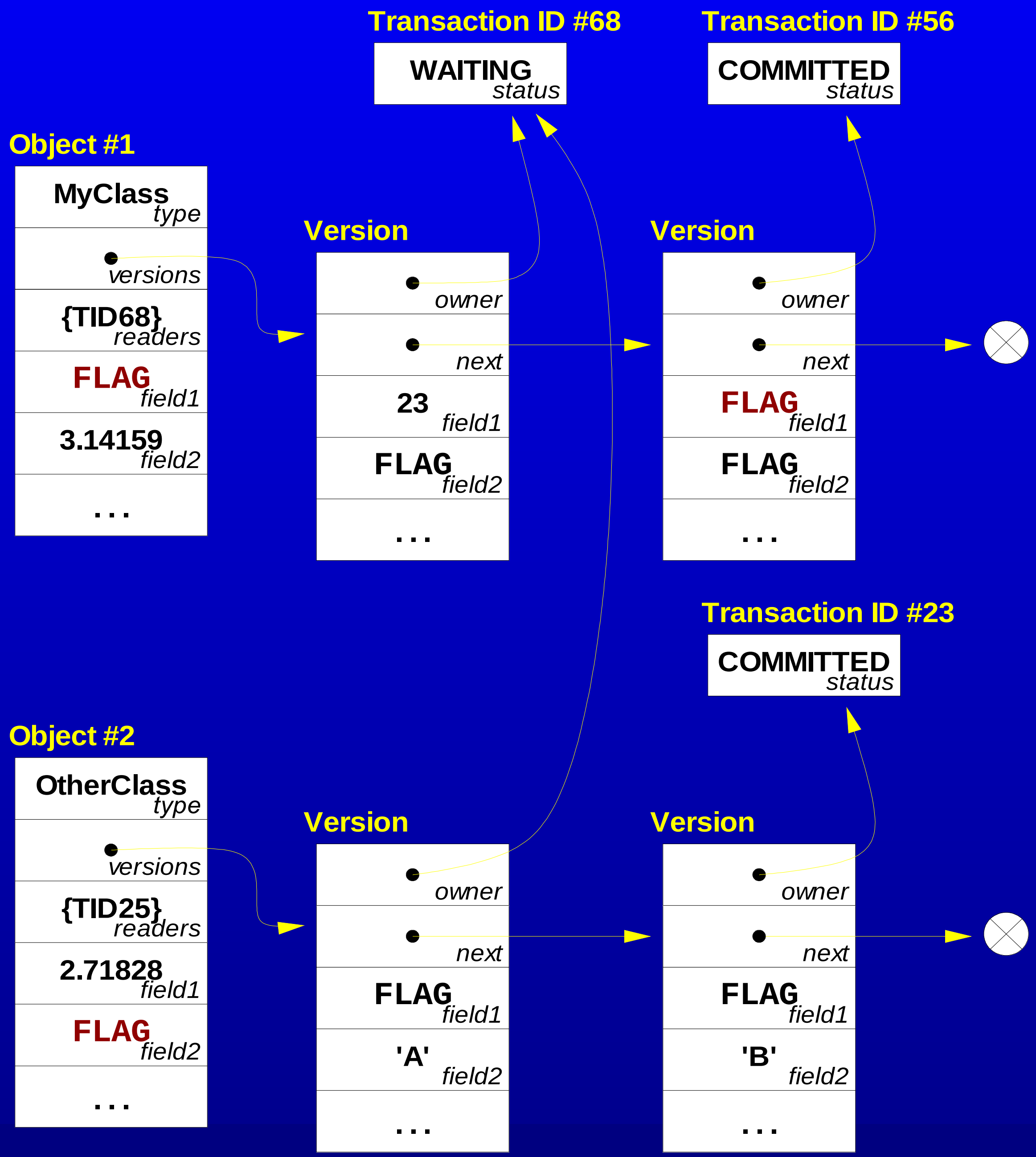
Making things practical: Things to keep in mind

- There is both transactional and non-transaction code in real systems
  - A robust mechanism won't allow violations of transactional atomicity
- Non-transactional code should be fast!
- Transaction duration may reach 100M memory operations
- Transactional reads out-number transactional writes 3 to 1

Software Transaction Implementation

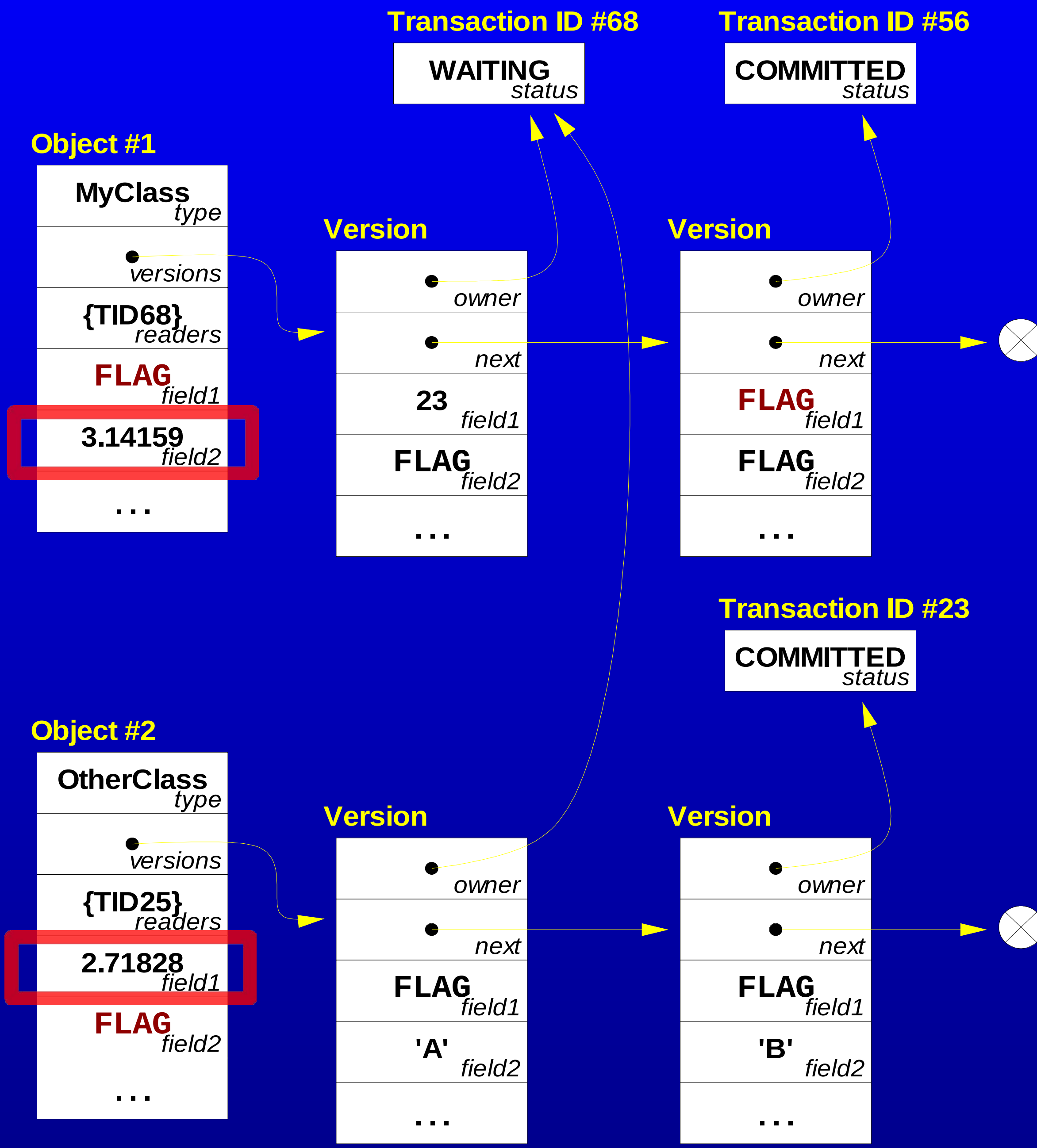
- **Goals:**
  - **Non-transactional operations should be fast**
  - **Reads should be faster than writes**
  - **Minimal amount of object bloat**
- **Solution:**
  - **Use special `FLAG` value to indicate "location involved in a transaction"**
  - **Object points to a linked list of versions, containing values written by (in-progress, committed, or aborted) transactions**
  - **Semantic value of `FLAG`ged field is: "value of the first version owned by a committed transaction on the version list"**
  - **Values which are "really" `FLAG` are handled with an escape mechanism (we call these "false flags")**

Transactions using version lists



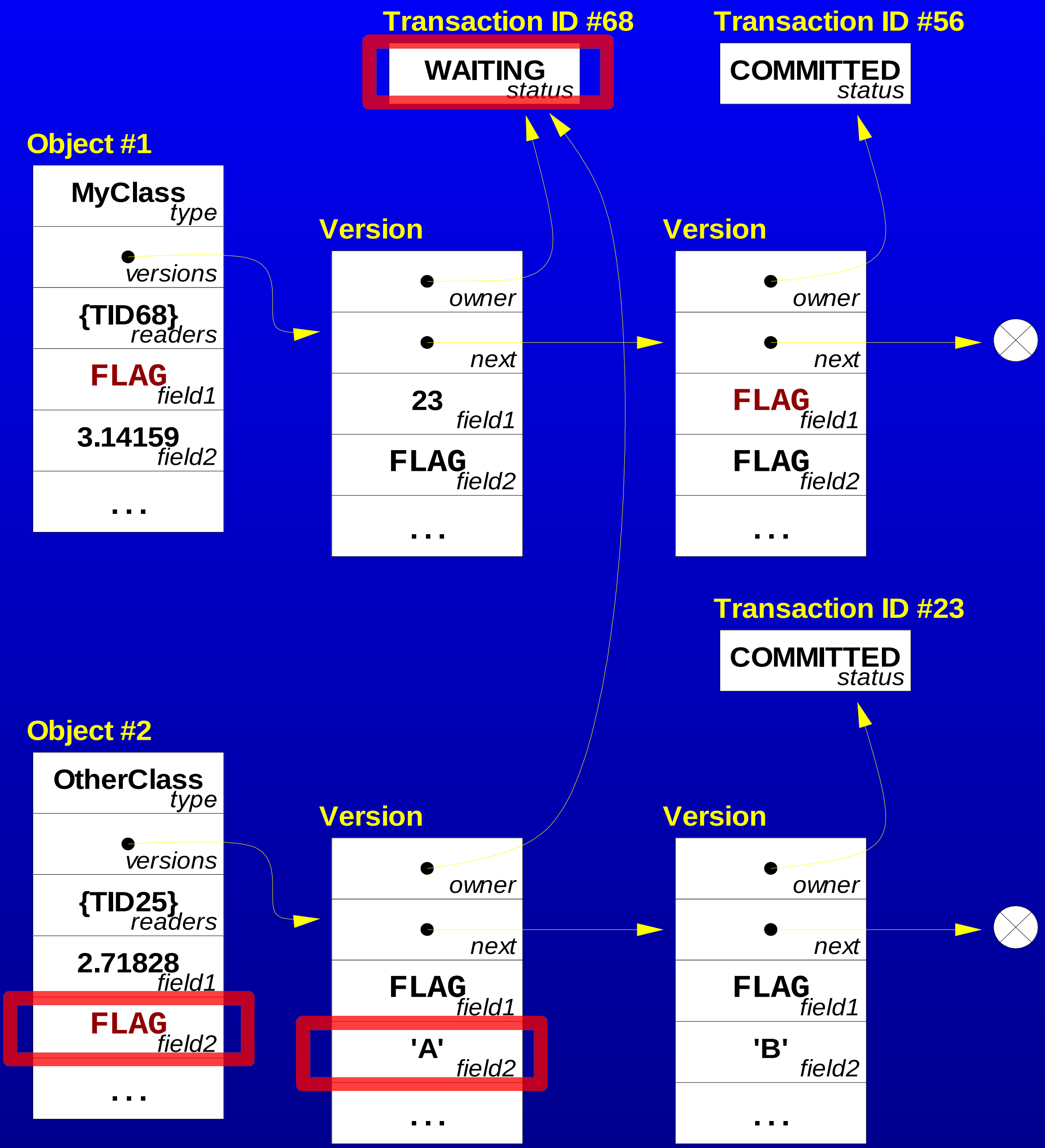
Non-transactional Read (ReadNT)

- **Begins with a normal read of the field.**
- **If value is not `FLAG`, we're done!**



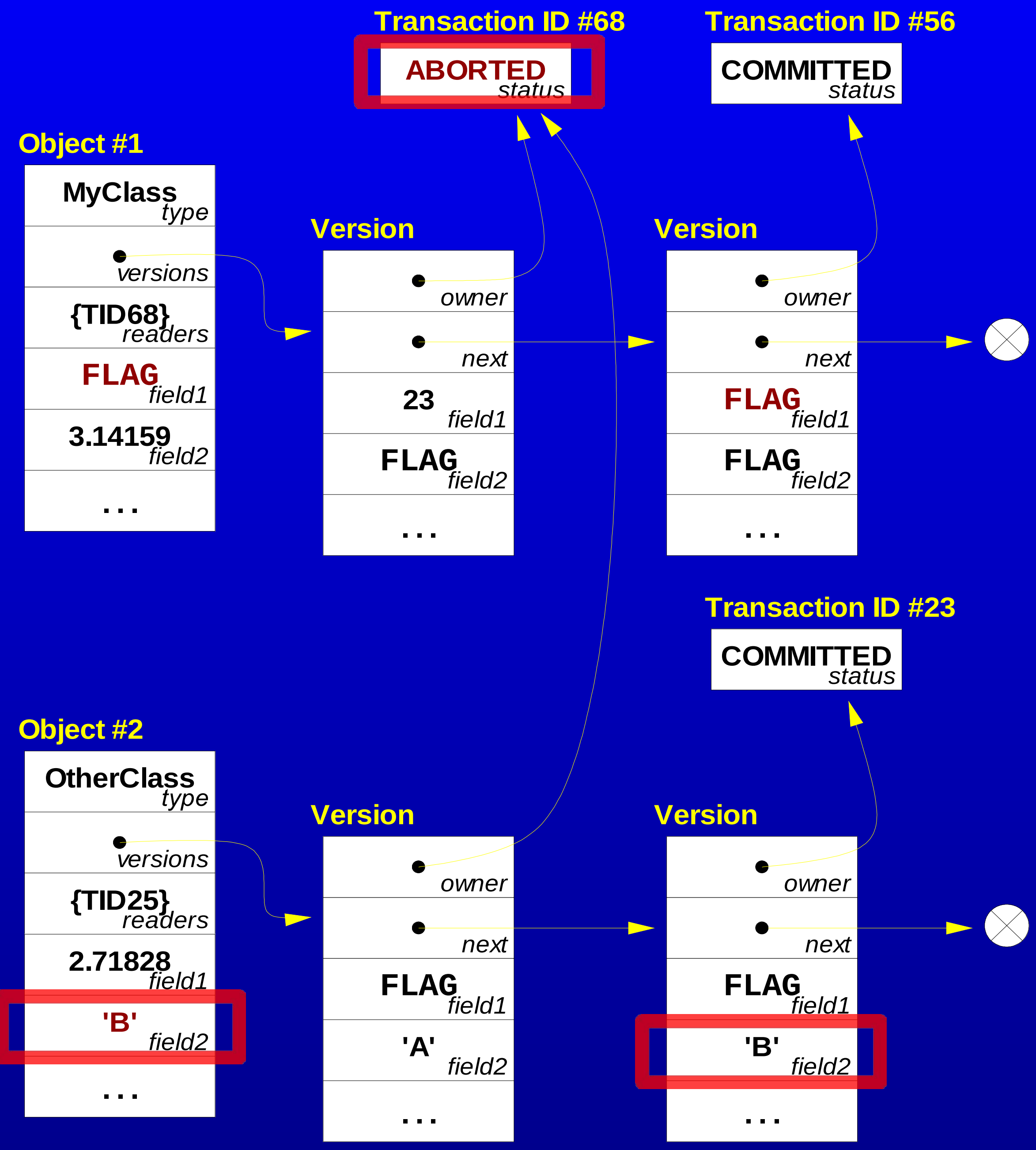
Non-transactional Read (ReadNT)

- **Begins with a normal read of the field...**
- **Otherwise:**
  - **kill writers**



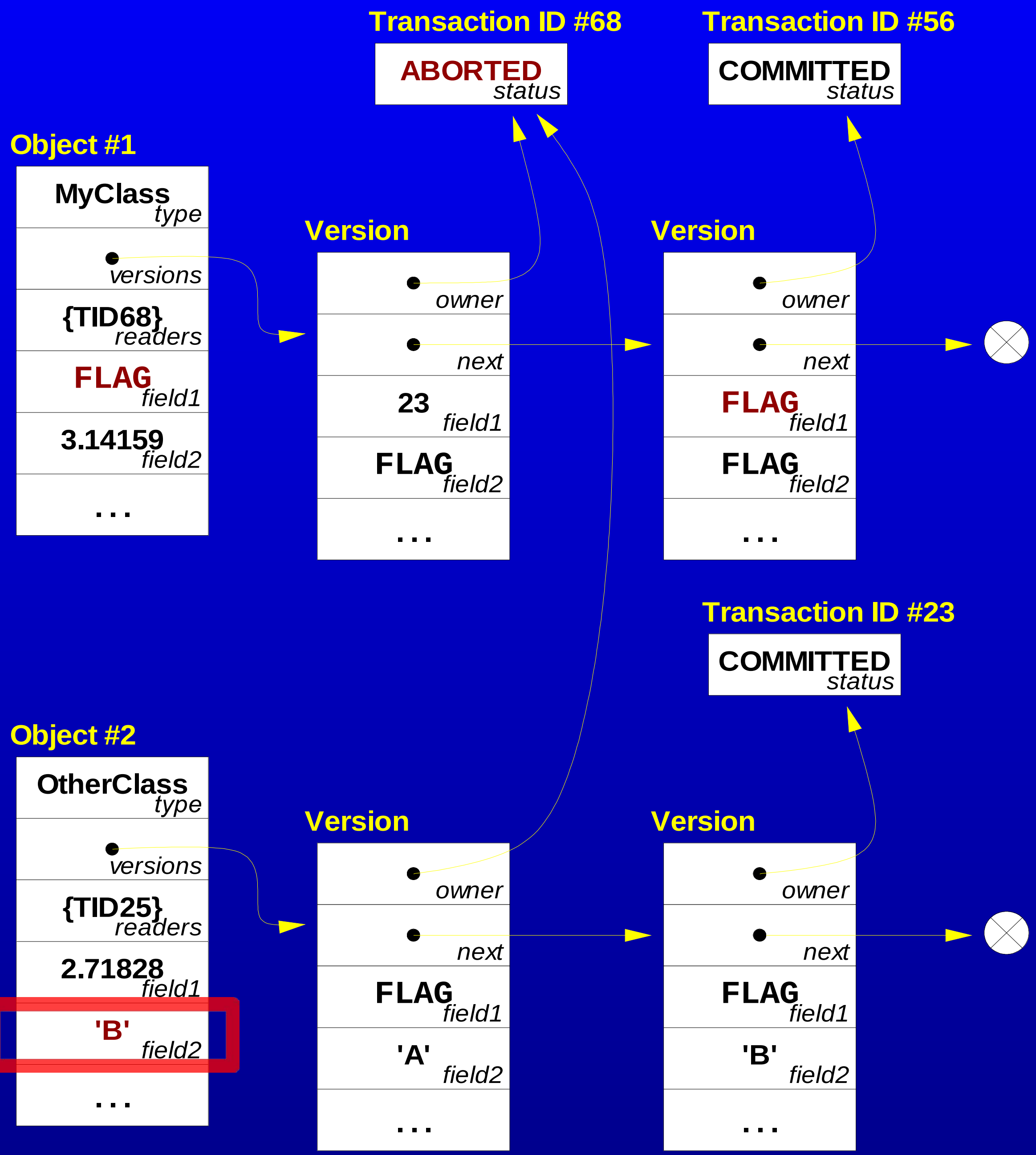
Non-transactional Read (ReadNT)

- Begins with a normal read of the field...
- Otherwise:
  - kill writers
  - copy back field



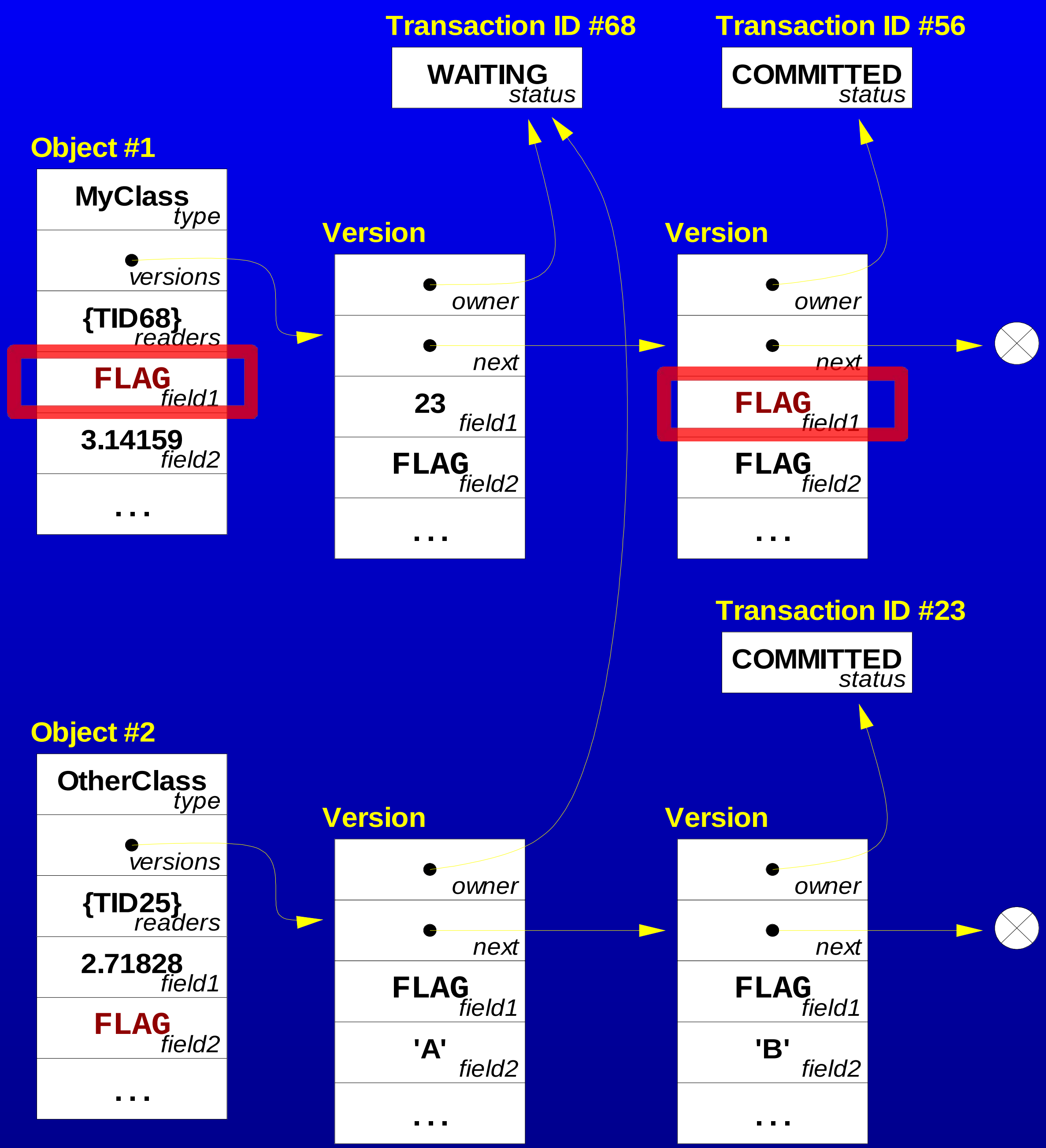
Non-transactional Read (ReadNT)

- Begins with a normal read of the field...
- Otherwise:
  - kill writers
  - copy back field
  - restart



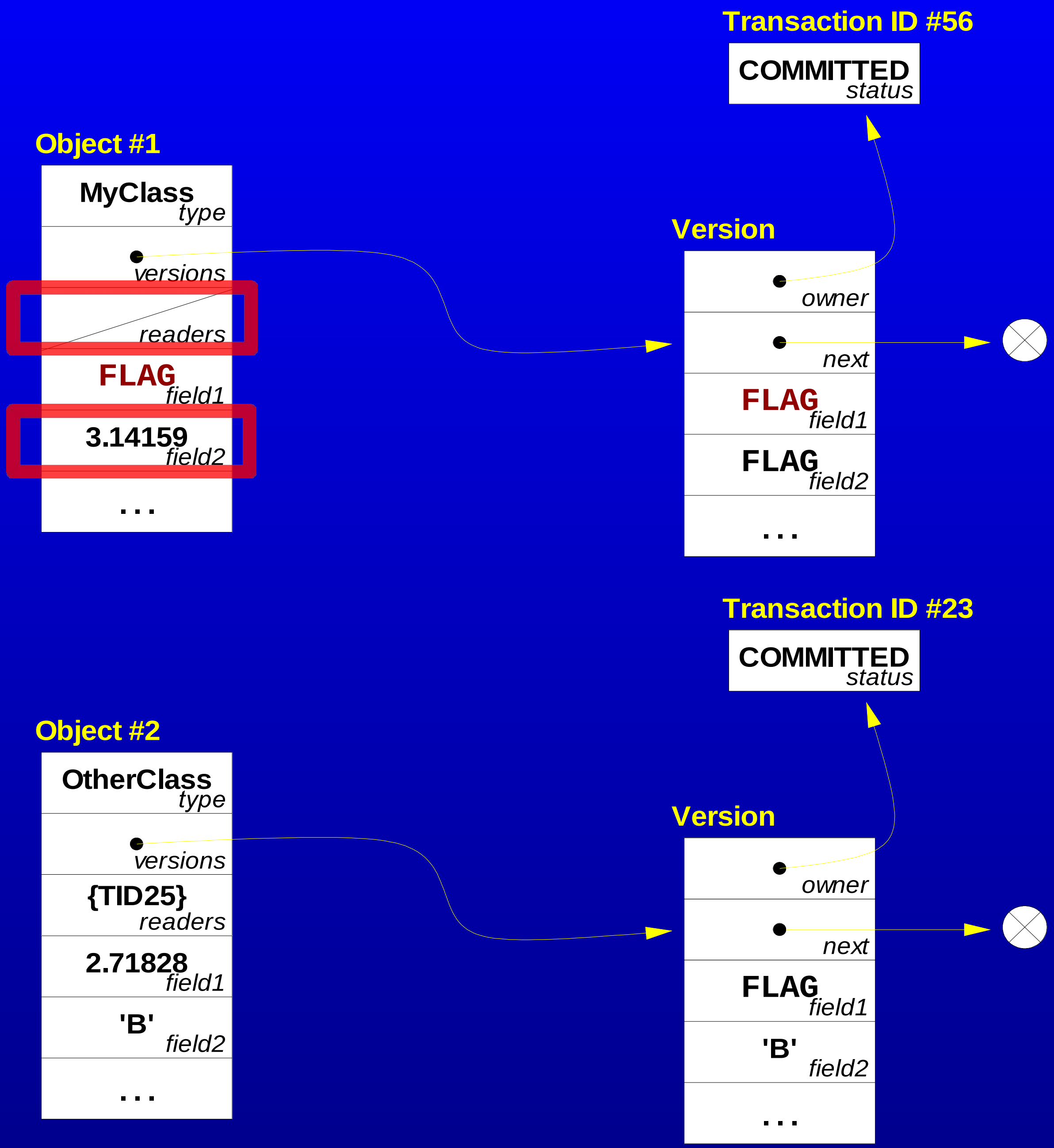
Non-transactional Read (ReadNT)

- Begins with a normal read of the field...
- "**False flags**" are discovered during copy-back; the read value is `FLAG` in this case.



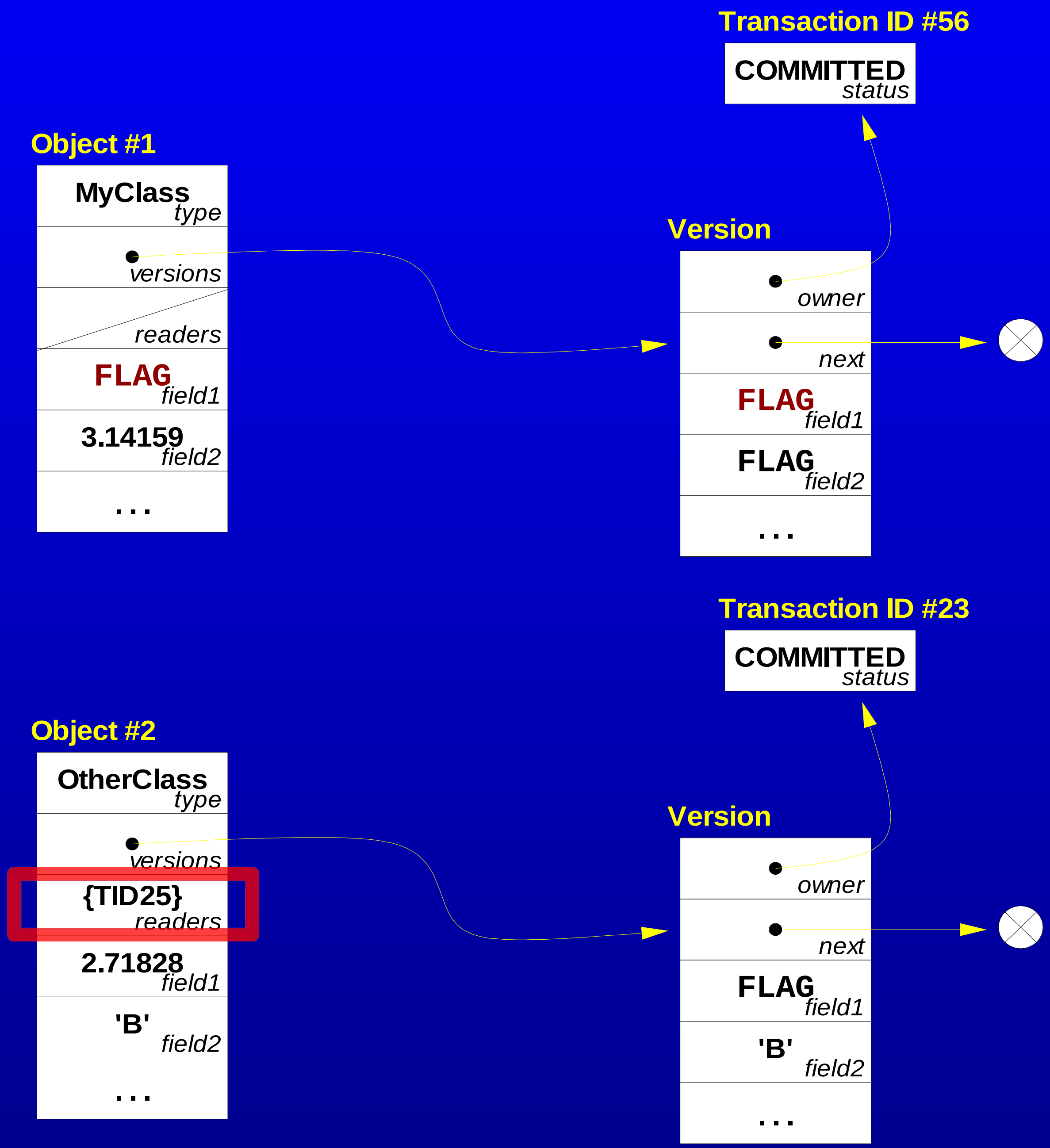
Non-transactional Write (WriteNT)

- If value-to-write is not `FLAG`:
  - LL(readers)
  - check that it's empty
  - SC(field)



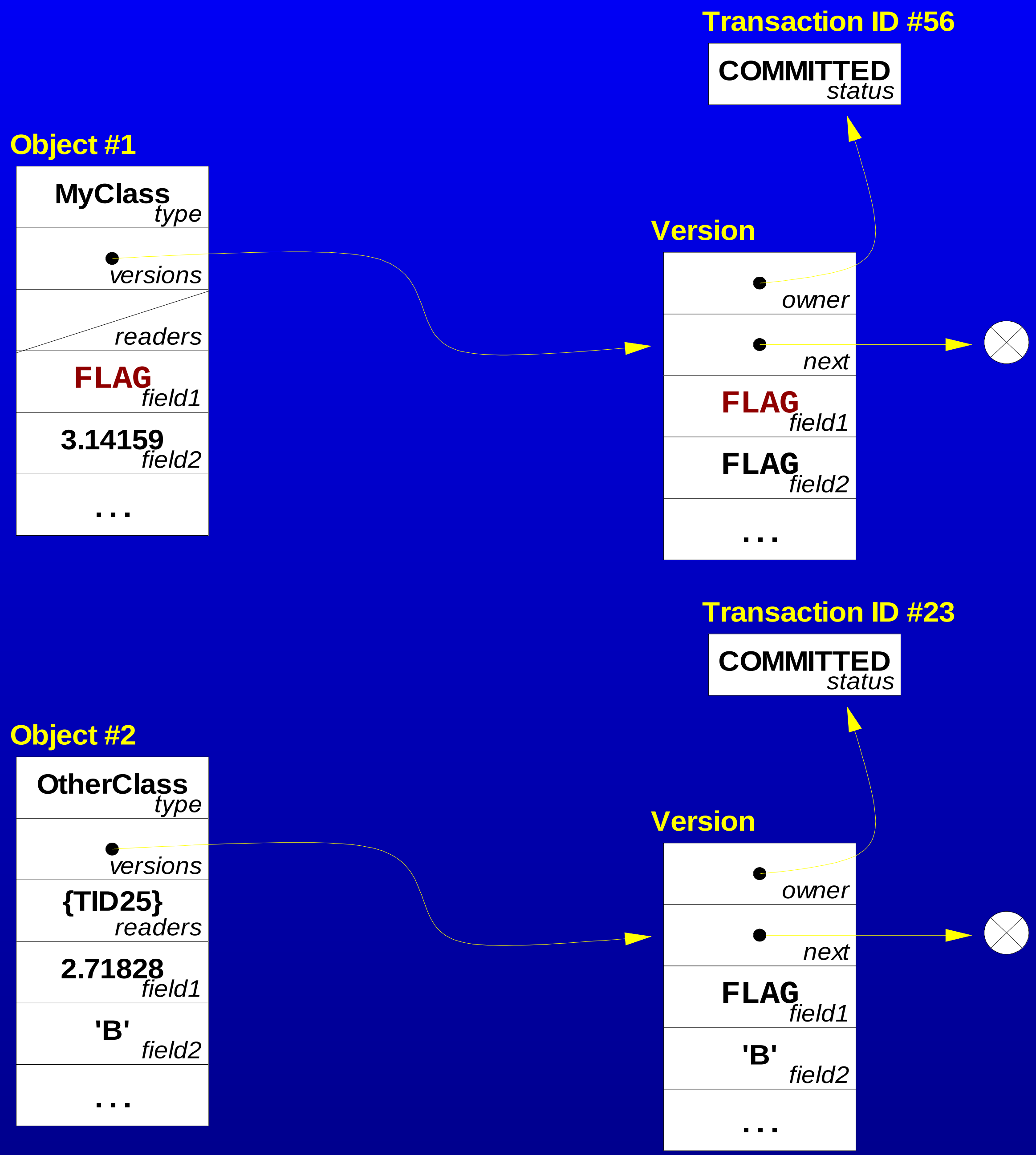
Non-transactional Write (WriteNT)

- If value-to-write is not `FLAG`:
  - LL(readers)
  - check that it's empty
  - SC(field)
- If unsuccessful
  - kill readers and writers
  - repeat



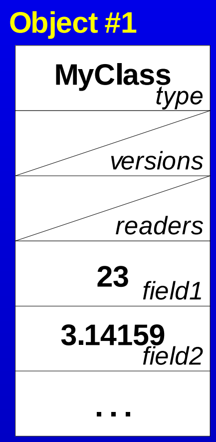
Non-transactional Write (WriteNT)

- If value-to-write *is* `FLAG`...
  - make this a short transactional write (WriteT)



Transactional Write (WriteT)

- ***Once*** **per object written in this transaction:**
  - **find writable version**
  - **create (by cloning) if necessary**
- **Analysis and rewriting can offer big wins**



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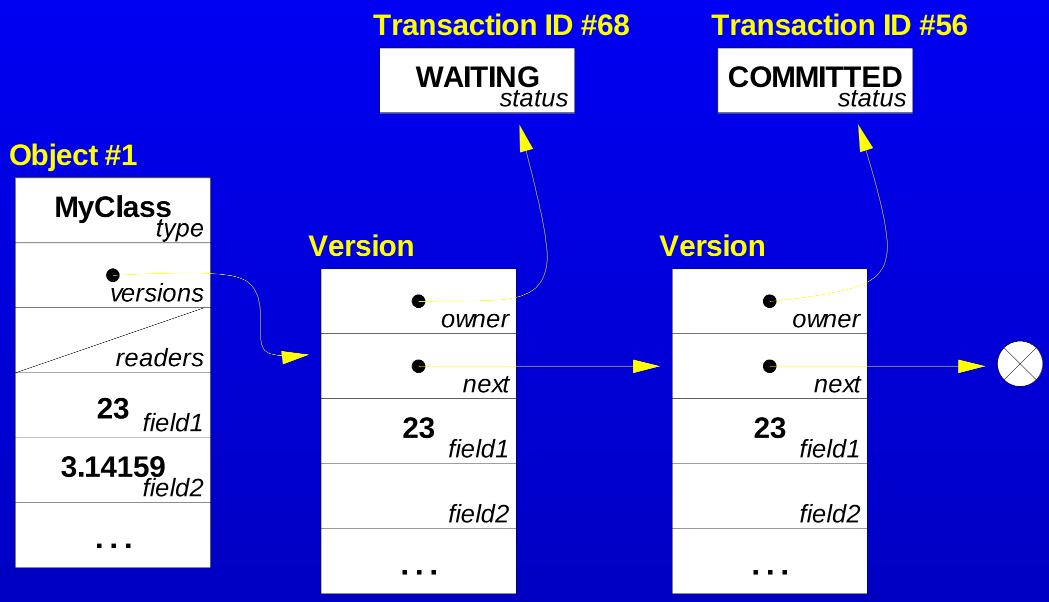

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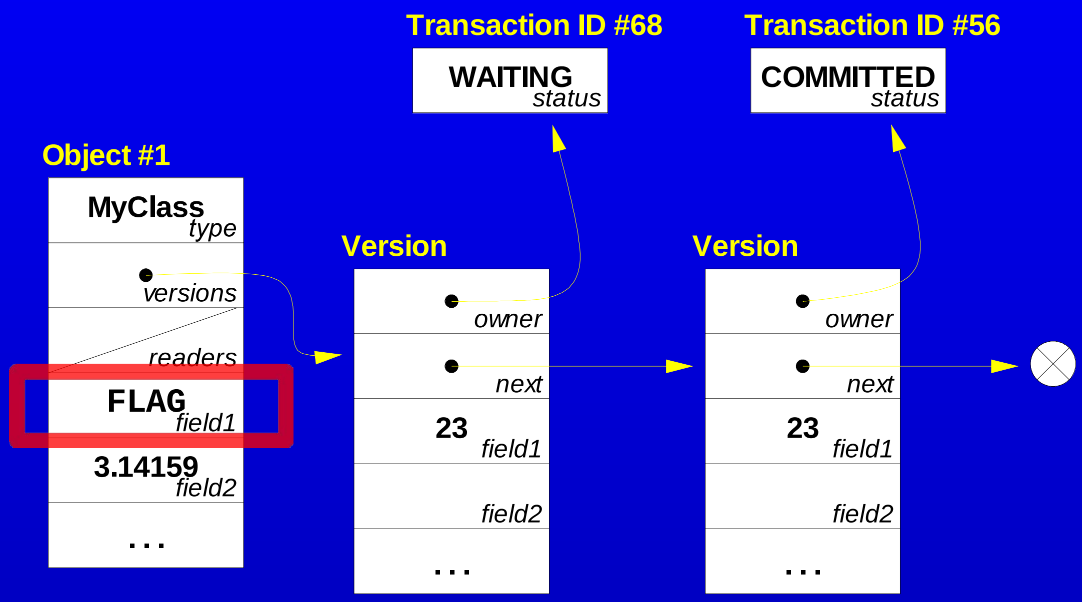
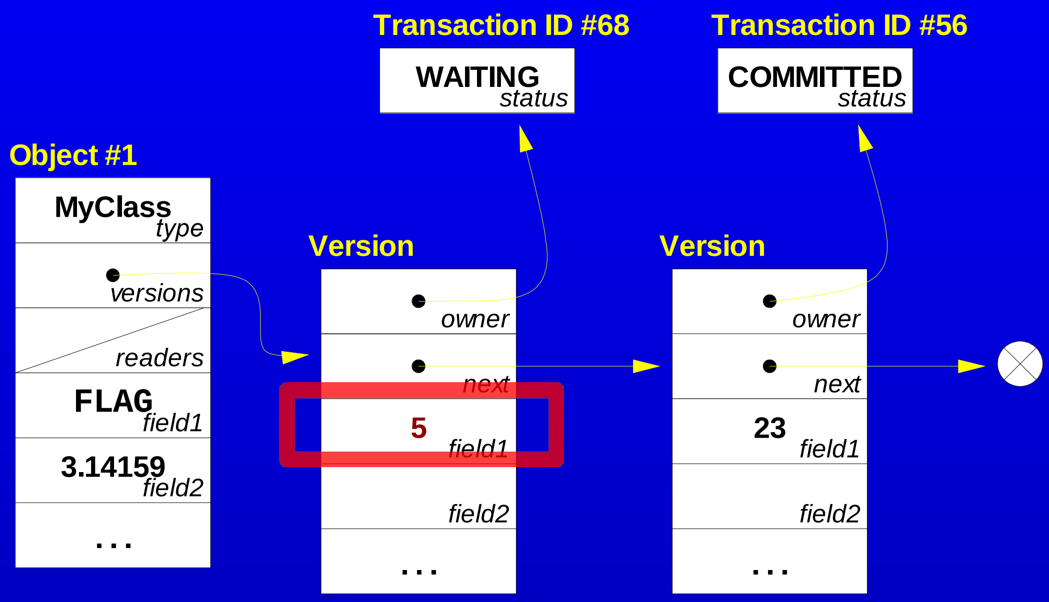


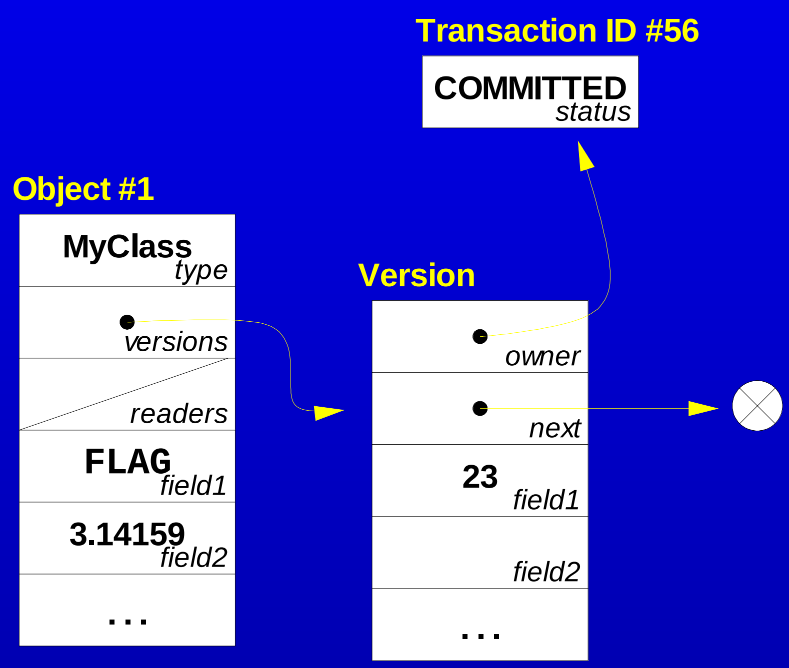
Transactional Write (WriteT)

- *Once* per object written in this transaction:
  - find writable version
  - create (by cloning) if necessary
- Analysis and rewriting can offer big wins
- Then, **just write to the version**.



Transactional Read (ReadT)

- ***Once*** **per object read in this transaction:**
  - **ensure we're on list of readers**
  - **kill any writers**



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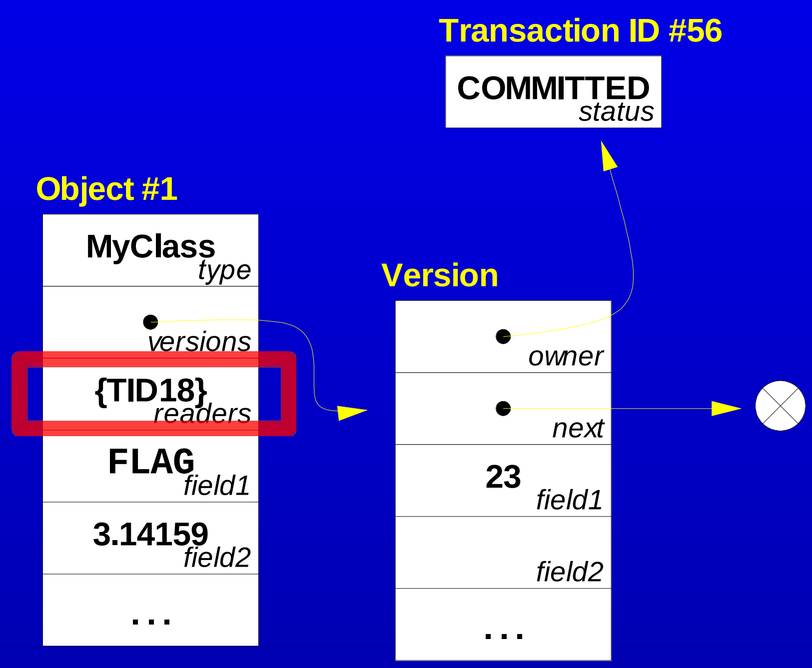
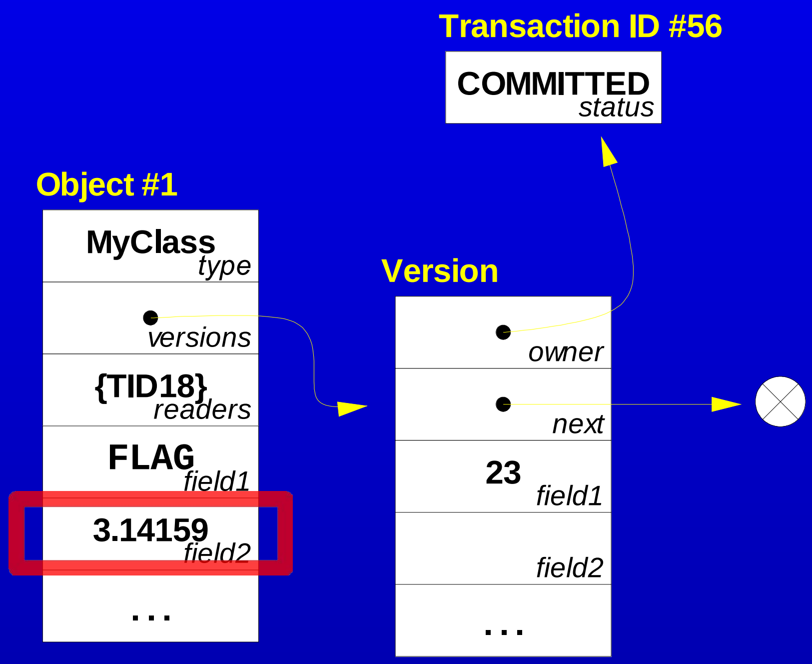


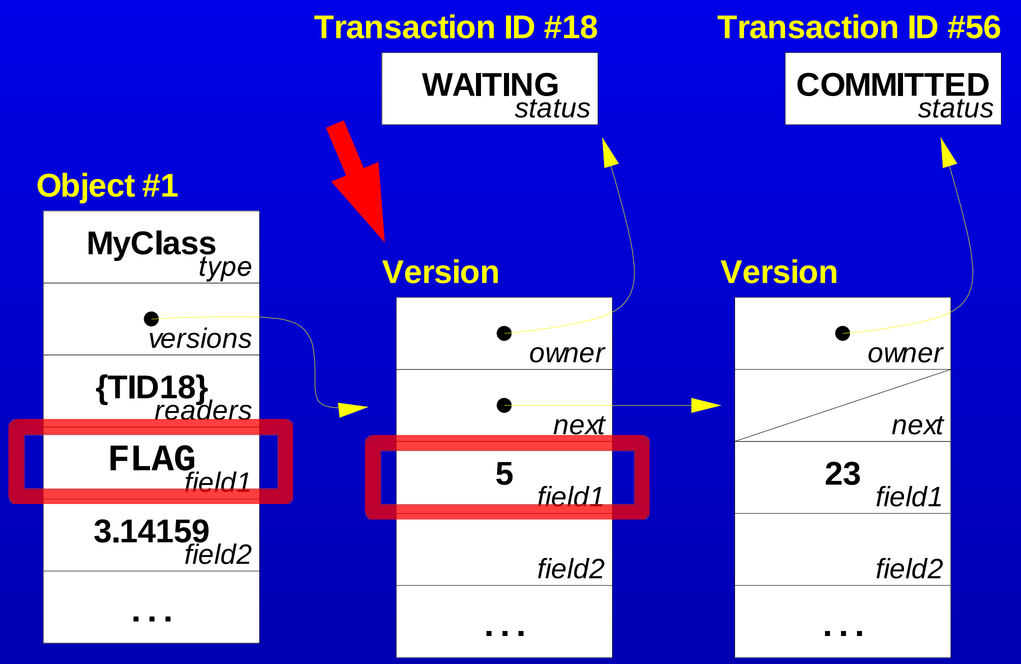
Transactional Read (ReadT)

- ***Once*** **per object read in this transaction:**
  - **ensure we're on list of readers**
  - **kill any writers**
- **Read field of object**
- **If this is not `FLAG`, you're done!**



Transactional Read (ReadT)

- ***Once*** **per object read in this transaction:**
  - **ensure we're on list of readers**
  - **kill any writers**
- **Read field of object**
- **If this is `FLAG`, then read field from version**
  - **remember version for next time!**



Performance

- Non-transactional code only needs to check whether a memory operand is `FLAG` before continuing.
  - On superscalar processors, there are plenty of extra functional units to do the check
  - The branch is extremely predictable
  - This gives only a few % slowdown
- Once `FLAG`ged, transactional code operates directly on the object's "version"
- Creating versions can be an issue for large arrays; use "functional array" techniques

Non-blocking concurrent algorithms are hard!

- **In published work on Synthesis, a non-blocking operating system implementation, three separate races were found:**
  - **One ABA problem in LIFO stack**
  - **One likely race in MP-SC FIFO queue**
  - **One interesting corner case in quaject callback handling**
- **It's hard to get these right! Ad hoc reasoning doesn't cut it.**
- **Non-blocking algorithms are too hard for the programmer**
- **Let's get it right once (and verify this!)**

Verification with Spin

- Modeled the software transaction implementation in Promela
- Low-level model – every memory operation represented
  - details in the paper
- Spin used 16G of memory to check the implementation within a 6-version 2-object scope.

The Spin Model Checker

- Spin is a model checker for communicating concurrent processes. It checks:
  - Safety/termination properties
  - Liveness/deadlock properties
  - Path assertions (requirements/never claims)
- It works on finite models, written the Promela language, which describe infinite executions.
- Explores the entire state space of the model, including all possible concurrent executions, verifying that Bad Things don't happen.
- Not an absolute proof – pretty useful in practice
- Make systems reliable by concentrating complexity in a verifiable component

Spin theory

- Generates a Büchi Automaton from the Promela specification.
  - Finite-state machine w/ special acceptance conditions
  - Transitions correspond to executability of statements
- Depth-first search of state space, with each state stored in a hashtable to detect cycles and prevent duplication of work
  - If *x* followed by *y* leads to the same state as *y* followed by *x*, will not re-traverse the succeeding steps
- If memory is not sufficient to hold all states, may ignore hashtable collisions: requires one bit per entry. # collisions provides approximate coverage metric

Bugs Found

- **Memory management**
  - **reference counting, object recycling**
- **Read caching**
  - **check freshness of copies in local variables**
- **“Big” bug**
  - **missing abort of readers during a non-transactional write (field copy back)**

Hybrid Hardware/Software Implementation

- **Hardware transaction implementation is very fast! But it is limited:**
  - **Slow once you exceed cache capacity**
  - **Transaction lifetime limits (context switches)**
  - **Limited semantic flexibility (nesting, etc)**
- **Software transaction implementation is unlimited and very flexible!**
  - **But transactions may be slow**
- **Solution: failover from hardware to software**
  - **Simplest mechanism: after first hardware abort, execute transaction in software**
  - **Need to ensure that the two algorithms play nicely with each other (consistent views)**

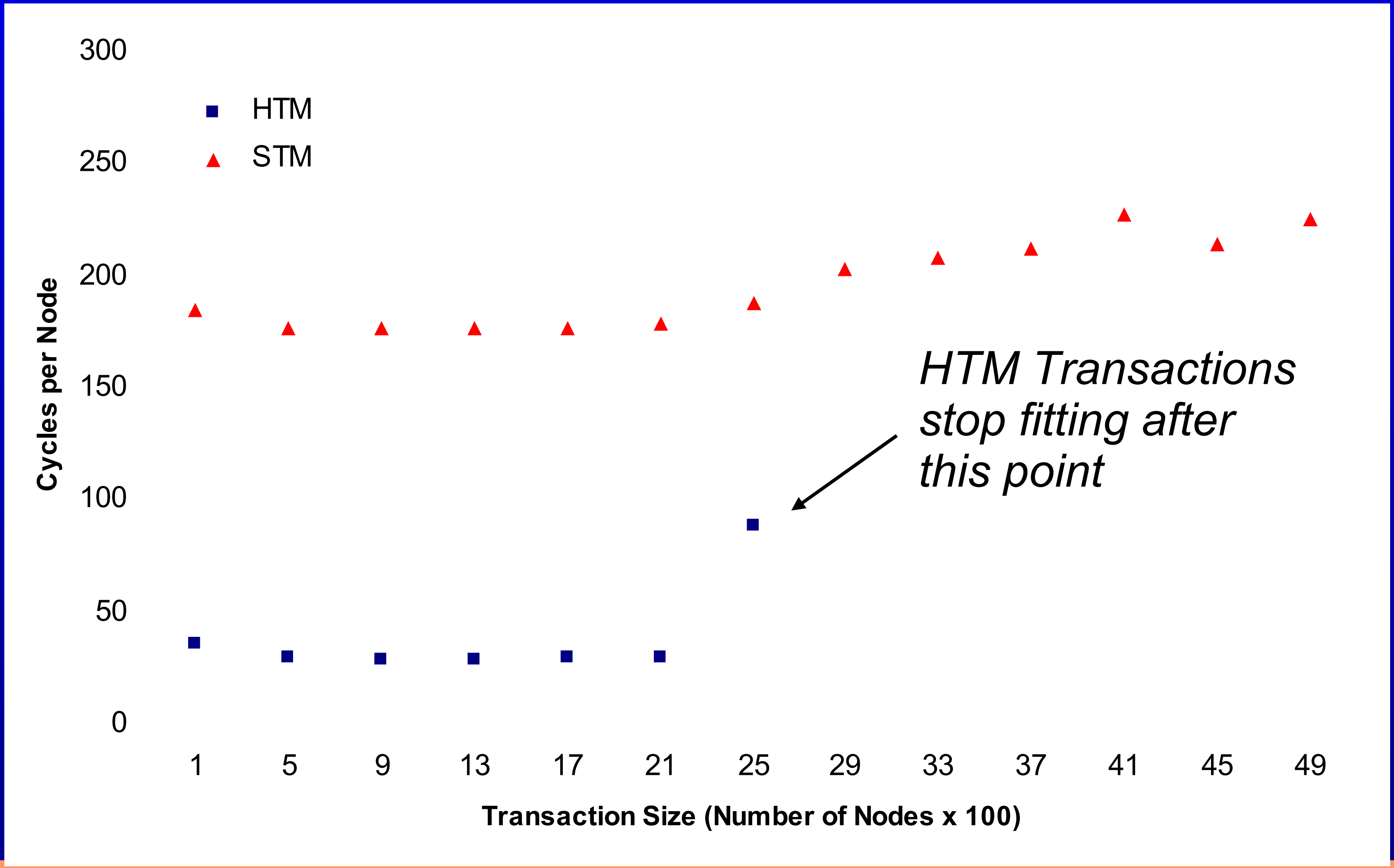
    ➔ see next slide...

Cooperation

- **Software transaction mechanism writing FLAG over object fields is sufficient to abort conflicting HTM**
- **HTM must execute ReadNT/WriteNT algorithms (read barrier) to cooperate with the software mechanism**
  - **no extra silicon needed!**
  - **can still leverage compiler analysis**
- **Other synergies:**
  - **non-blocking functional array implementation**
  - **LL/SC sequences**

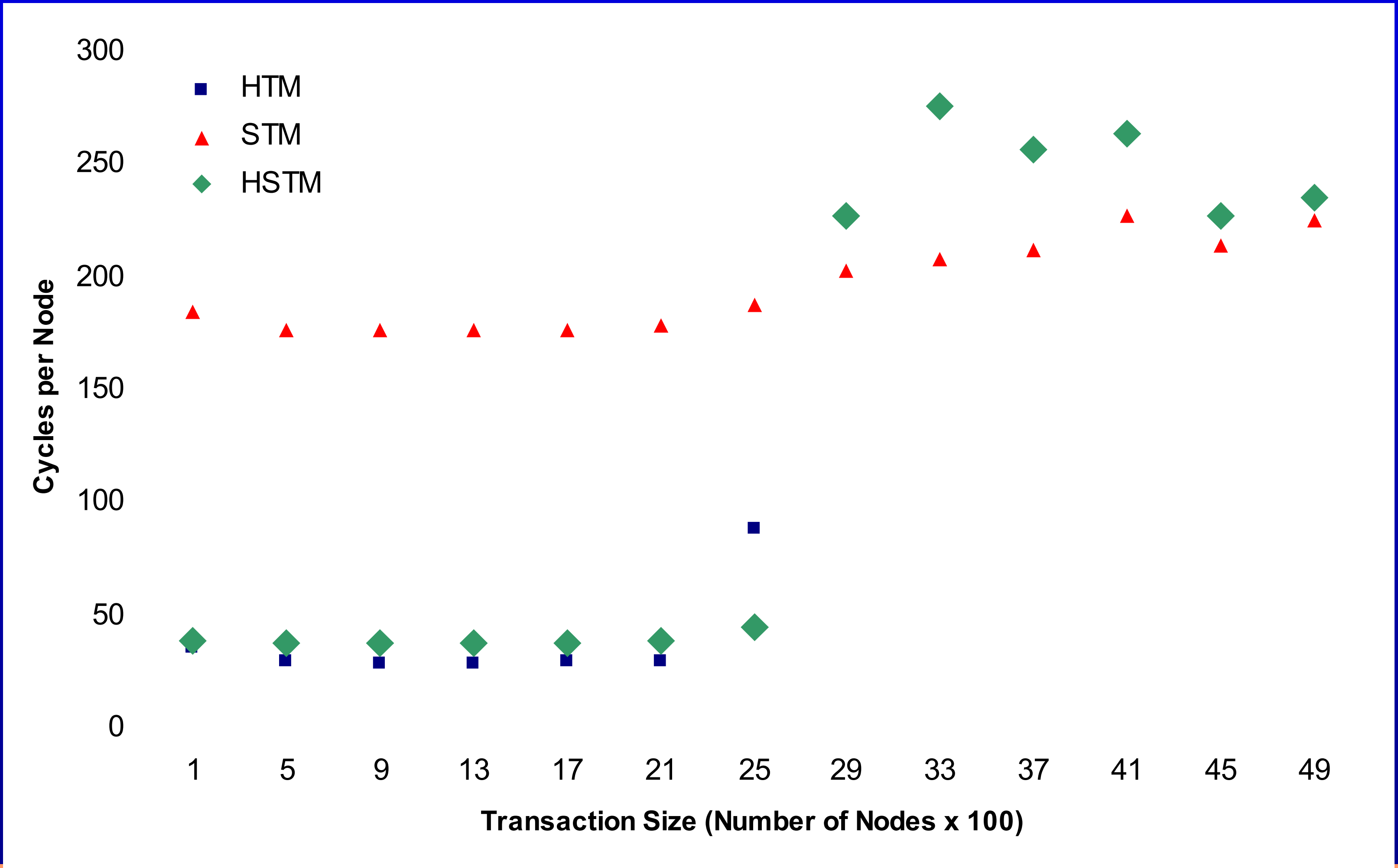
Leveraging hardware for speed

- **Simple node-push benchmark [Lie '04]**
- **As xaction size increases, we eventually run out of cache space in the HW transaction scheme**



Leveraging hardware for speed

- **Simple node-push benchmark [Lie '04]**
- **Hybrid scheme best of both worlds!**



Conclusions

- **Transactional/non-transactional cooperation is really a lot like STM/HTM cooperation**
  - **same mechanism can be used!**
- **The Large Object Problem can be solved!**
  - **Good news for object-based transactions**
  - **Compiler and analysis benefits to reap**
- **Writing correct transaction protocols is hard**
  - **Model checking can help**

Thank you!

(p.s. I'm graduating soon!)