Improving the Java Memory Model Using CRF

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Java Memory Model: Problems

- **Incomplete**
  - ***No semantics for final fields***
- **Disallows important optimizations**
  - ***Reordering of loads to same location***
  - ***Some reordering are inexpressible in source***
- ***Difficult to understand***
  - ***Memory updates not atomic***

Roadmap

- **Examples of JMM problems**
- **Desired Programming Discipline**
  - **Well-behaved programs**
  - **Source-level algebraic reasoning**
- **Translating Java into CRF**
- **Conclusions**

Final fields: The String Example

Thread 1

```
char [ ] a = {'H','i'};
s = new MyString(a);
```

Thread 2

```
print(s);
```

Thread 2 should either print "Hi" or throw an exception

```
class MyString {
        private final char[ ] theCharacters;
        public MyString( char[ ] value) {
            char[ ] internalValue = value.clone();
            theCharacters = internalValue;
        }
        ...
}
```

Enabling Optimizations

Thread 1

v = p.f;

w = q.f;

x = p.f;

Thread 2

p.f = 2;

Can we replace x = p.f by x = v ?

- ***Old JMM: No!***

  What if p==q? Reads must be ordered!

- ***Proposed JMM: Yes!***

  Reads can be reordered

Confusing Semantics

v = q.g;
w = p.f;
p.f = 42;
	_	w = p.f;
		p.f = 42;
		v = q.g;

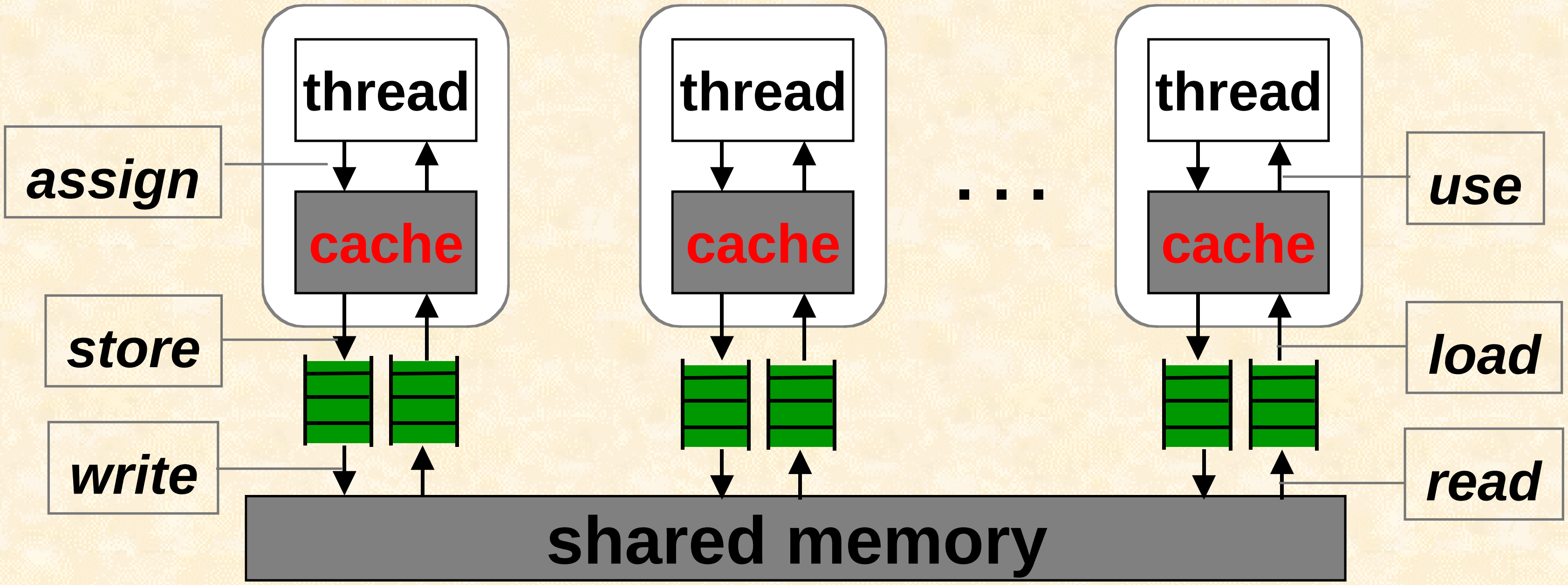
u = p.f;
v = q.g;
w = p.f;
p.f = 42;
	X	u = p.f;
		w = p.f;
		p.f = 42;
		v = q.g;

Program behavior is context-sensitive [Pugh99]

The old JMM semantics are simply too convoluted!

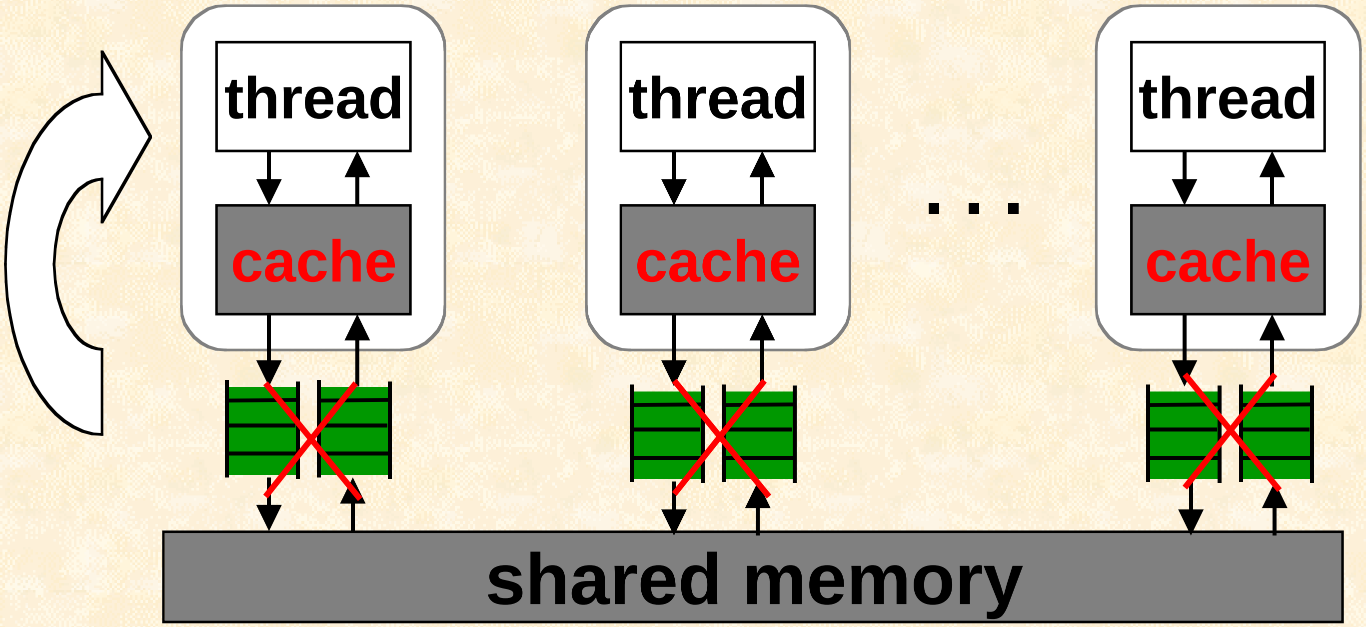
The Java Memory Model

[Gosling, Joy, Steele, 1st ed., Ch 17]



- Seven axioms define permitted reorderings
  - use and assign occur in program order
  - store and write to a location occur in order
  - read and load from a location occur in order

Solution: Make Reorderings Explicit



Reorder at the thread level
Make instructions atomic

Plan of action

- Define a desired programming style for Java
- Give high-level description of program behavior
- Capture high-level description in a precise semantics

Java Memory Operations

- ***Regular Memory***

  v = LoadR p.f **StoreR p.f,v**

- ***Volatile Memory***

  v = LoadV p.f **StoreV p.f,v**

- ***Final Memory***

  v = LoadF p.f **StoreF p.f,v**

  EndCon

- ***Monitors***

  Enter l **Exit l**

Regular fields

Constrained only by data dependence

- Load/Store must be protected by monitors
  - If it's shared, it must be locked during access
- Read-only objects can omit synchronization
  - But only when reached through final fields

Final Fields and Constructors

Allow creation of read-only data

- An object must not escape its constructor

- Final fields may be read without synchronization
  - Includes referenced read-only objects

Volatile Fields

Allow free-form data exchange

- **Volatile operations occur in program order**
- **Volatile loads act like Enter**
- **Volatile stores act like Exit**
- **Any field may safely be made volatile**

Algebraic Rules

- Source-to-source program manipulation
  - See the effects of reordering
  - Reason about incorrect program behavior
- Captures legal static reorderings
- Easy to reason about interleaved execution
- Implied by dynamic semantics

Load/Store Reordering

- Must respect usual dependencies:

  Store p.f,4; x = Load p.f; Store p.f,5;

- Regular & Final operations reorder freely:

StoreR p.f,4;	y = LoadF q.g;
x = LoadF q.g;	x = LoadF q.g;
y = LoadF q.g;	StoreR p.f,4;

- Volatile operations do not reorder!

Synchronization

- Any Load/Store may enter synchronization

LoadR q.f;	Enter p.l;
Enter p.l;	LoadR q.f;
LoadR p.f;	LoadR p.f;
Exit p.l;	LoadR q.g;
LoadR q.g;	Exit p.l;

- Non-finals may not escape synchronization
- Enter must be ordered wrt both Enter and Exit.

Other Interactions

- LoadV acts like Enter, StoreV acts like Exit

LoadR q.f;	LoadV p.v;
LoadV p.v;	LoadR q.f;
LoadR p.f;	LoadR p.f;
StoreV p.v;	LoadR q.g;
LoadR q.g;	StoreV p.v;

- EndCon keeps stores in, non-final stores out:

StoreF p.f, 5;	StoreF p.f, 5;
EndCon;	StoreF q.g, p;
StoreF q.g, p;	EndCon;
StoreR r.h, p;	StoreR r.h, p;

Reordering Around Control Flow

Thread 1

```
int tmp1 = p.flag;
if (tmp1==1) {
    int tmp2 = p.flag;
    system.out.print("yes");
    if (tmp2 == 0) {
      system.out.print("BAD");
    }
}
```

Thread 2

```
p.flag = 1;
```

Consequence of poor synchronization

Compilation

- ***Dependency Analysis* = Reordering**
  - **Read/write constraints don't capture reorderings**
- ***Type & alias analyses* permit read/write reordering**
  - **Regular, volatile, and final storage are disjoint!**
- ***Escape analysis* permits local operation reordering**
- ***Pointer analysis* spots fetches via final pointers**

Roadmap

- Examples of JMM problems
- Desired Programming Discipline
  - Well-behaved programs
  - Source-level algebraic reasoning
- **Translating Java into CRF**
- Conclusions

CRF: A General Representation

Java Threads

(regular, final, volatile, monitors)

Commit-Reconcile & Fences (CRF)

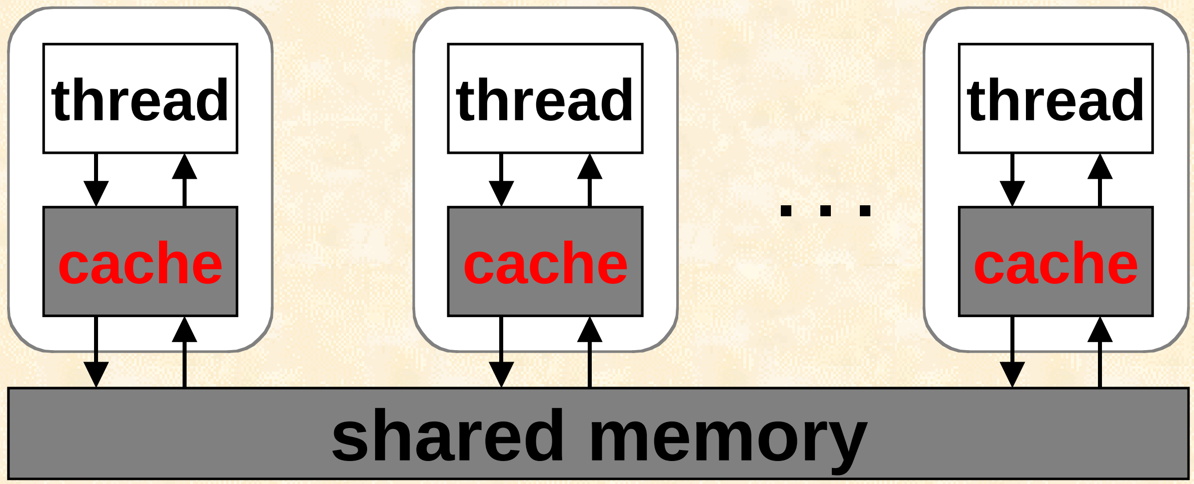
X86 *Sparc* *PowerPC* *Alpha*

(Shen, Arvind, Rudolph, ISCA99)

Java to CRF: Regular Memory

x = LoadR p.f;	_	Reconcile p.f; x = LoadL p.f;
StoreR p.f, y;	_	StoreL p.f, y; Commit p.f;

The CRF Model



- ***data caching via semantic caches***
  - ***Cache updates at any time (background)***
  - ***Commit, Reconcile*** **force** ***updates***
- ***instruction reordering*** **(controllable via Fence)**
- ***all operations act atomically***

The Fence Operations

Instructions can be reordered except for

- **Data dependence**
- **StoreL a,v; Commit a;**
- **Reconcile a; LoadL a;**

StoreL(a_1, v);
Commit(a_1);
Fence$_{wr}$ (a_1, a_2);
Reconcile(a_2);
LoadL(a_2);

Fence$_{rr}$; Fence$_{rw}$; Fence$_{ww}$;

Important Properties of CRF

- **Safe to add extra Commits & Reconciles**
- **Safe to add additional Fence operations**

Extra operations reduce exhibited behaviors, but preserve correctness

Can use coarse-grain operations, e.g:

Fence_{rr} p.f, *V; **Fence_{rr} p.f, *VR;**

Fence_{ww} l, *VRL; **Fence_{ww} *, *VR;**

Java to CRF: Final Memory

StoreF p.f, x;	–	StoreL p.f, x; Commit p.f; Freeze p.f;
y = LoadF p.f;	–	Reconcile p.f; y = LoadL p.f; Freeze p.f;

Java to CRF: Volatile Memory

x = LoadV p.f;	–	Fence_{rr} *V, p.f; Fence_{wr} *V, p.f; Reconcile p.f; x = LoadL p.f; Fence_{rr} p.f, *VR; Fence_{rw} p.f, *VR;
StoreV p.f, y;	–	Fence_{rw} *VR, p.f; Fence_{ww} *VR, p.f; StoreL p.f, y; Commit p.f;

Java to CRF: Synchronization

Enter l;	–	**Fence$_{ww}$ *L, l;** **Lock l;** **Fence$_{wr}$ l, *VR;** **Fence$_{ww}$ l, *VRL;**
Exit l;	–	**Fence$_{ww}$ *VR, l;** **Fence$_{rw}$ *VR, l;** **Unlock l;**
EndCon;	–	**Fence$_{ww}$ *,*VR;**

Allowing Lock Elimination

Enter l; –

```
Fence_ww *L, l;
r = Lock l;
if (r!= currentThread) {
    Fence_wr l, *VR;
    Fence_ww l, *VRL;
}
```

- Operations move upward out of lock region
  - Including into preceding lock regions
- Operations cannot move downward

Limits on Reordering

- Some reordering must be dynamic
  - Potential aliasing
- Some reordering is probably purely static
  - Based on analysis
- The boundary of static reordering is fuzzy

  a[x*x*x + y*y*y]   a[z*z*z]
- Solution: Flexible dynamic translation

Memory Model Issues Remaining

- **Speculation**
  - **Arbitrary value speculation is the limit point**
  - **Reordering around control gives us a lot**
  - **Points between difficult to formalize**
  - **Biggest open area in memory models**

- **G-CRF allows non-atomic Commit**

  No change in translation needed
  - **Is it necessary?**
  - **Can it be understood**

Other Memory Models

- **Data-Race-Free and Properly Labeled programs**
  [Adve & Gharachorloo, ...]
  - **Define a programming style**
  - **Appearance of sequential consistency**

- **Location consistency**
  [Gao & Sarkar, ...]
  - **Order writes per-thread & per-location**
  - **Set of possible values at each load**

Java Issues Remaining

- Run-time system memory model issues
  - New threads start with parent's state
  - GC responsible for its own synchronization
  - EndCon for object pre-initialization
- Thread-safe Library code
  - Code libraries correctly
  - Clarify finalization
  - Fix native code mutating final fields
- Establishing thread-safe Patterns
  - Lock-free caching (double-checking breaks)
  - Freezing mutable objects (Java Beans)

Java Memory Model in CRF

- **Precise and easy to understand**
  - *- Reason about reordering at instruction level*
  - *- Intuitive high-level semantics*
- **Flexible**
  - *- Easy to experiment with possible translations*
- **Makes optimizations obvious**
  - *- Reordering expressible in source*
- **Simple mapping to a variety of architectures**

Acknowledgements

- Bill Pugh
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- Vivek Sarkar & the Jalapeno group
- The readers of the JMM mailing list

Question Slides

Another Try

Thread 1

```
List q = p.next;
if (q == p) {
    List tmp = p.next;
    system.out.print("y");
    List r = tmp.next;
    if (r == null) {
        system.out.print("es");
    }
}
```

Thread 2

```
p.next = p;
```

Another Try

Thread 1

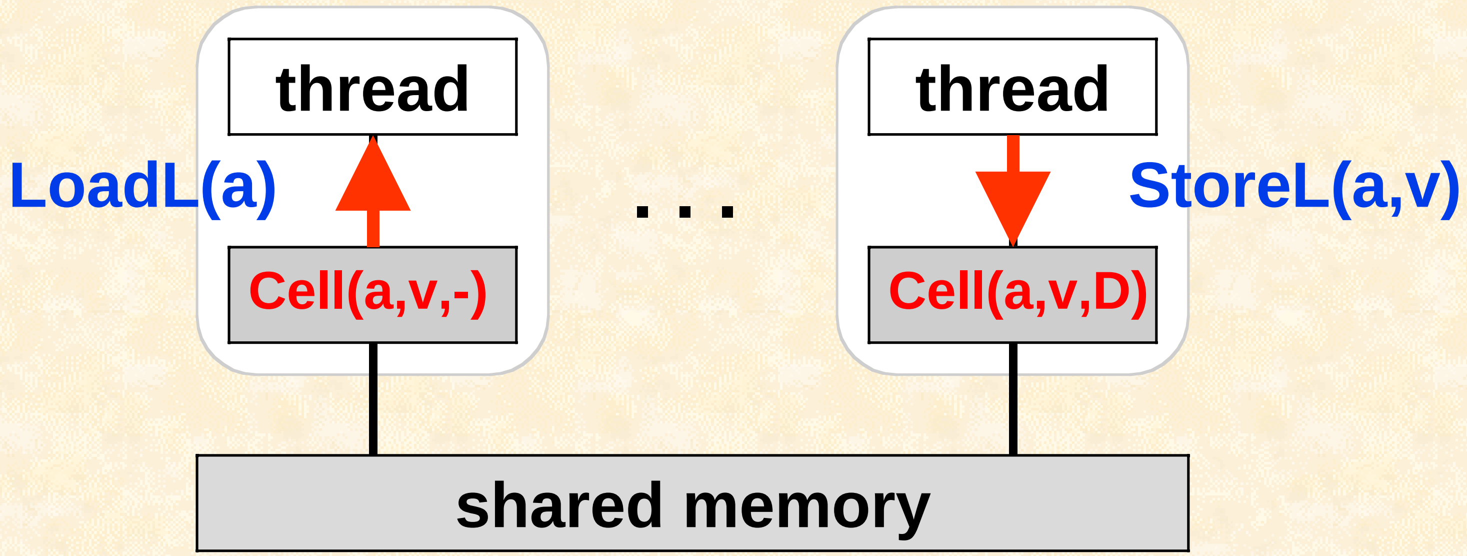
```
List r = p.next;
List q = p.next;
if (q == p) {
    system.out.print("y");

    if (r == null) {
        system.out.print("es");
    }
}
```

Thread 2

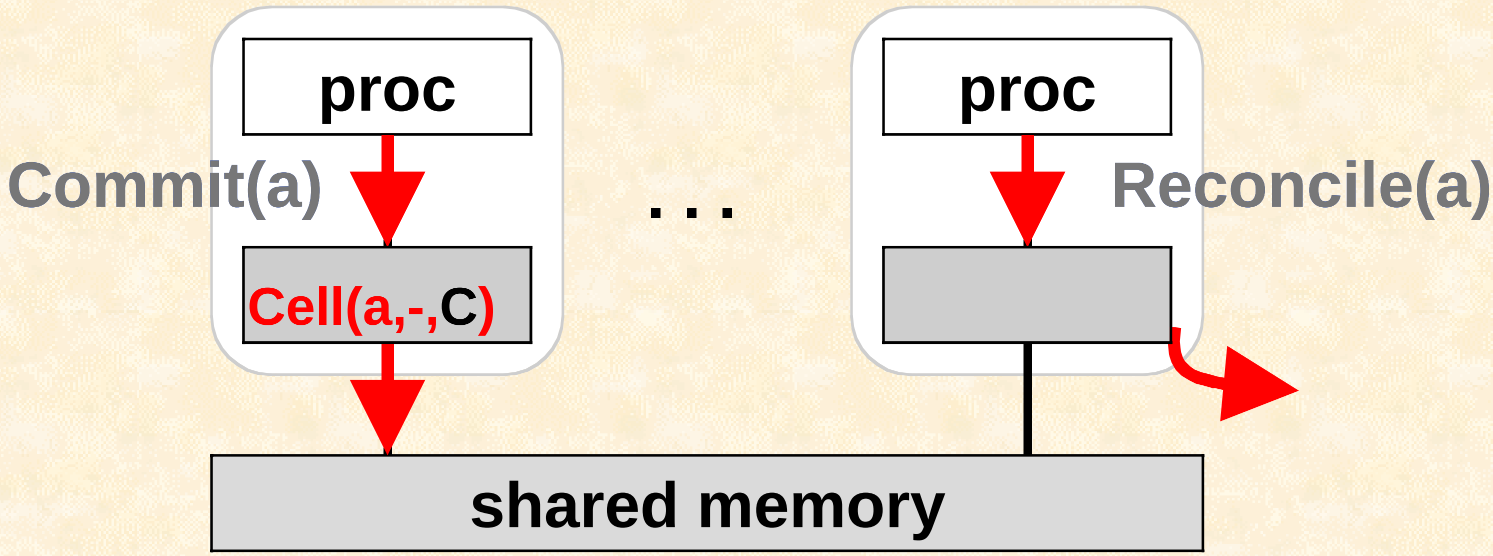
```
p.next = p;
```

CRF: LoadL and StoreL



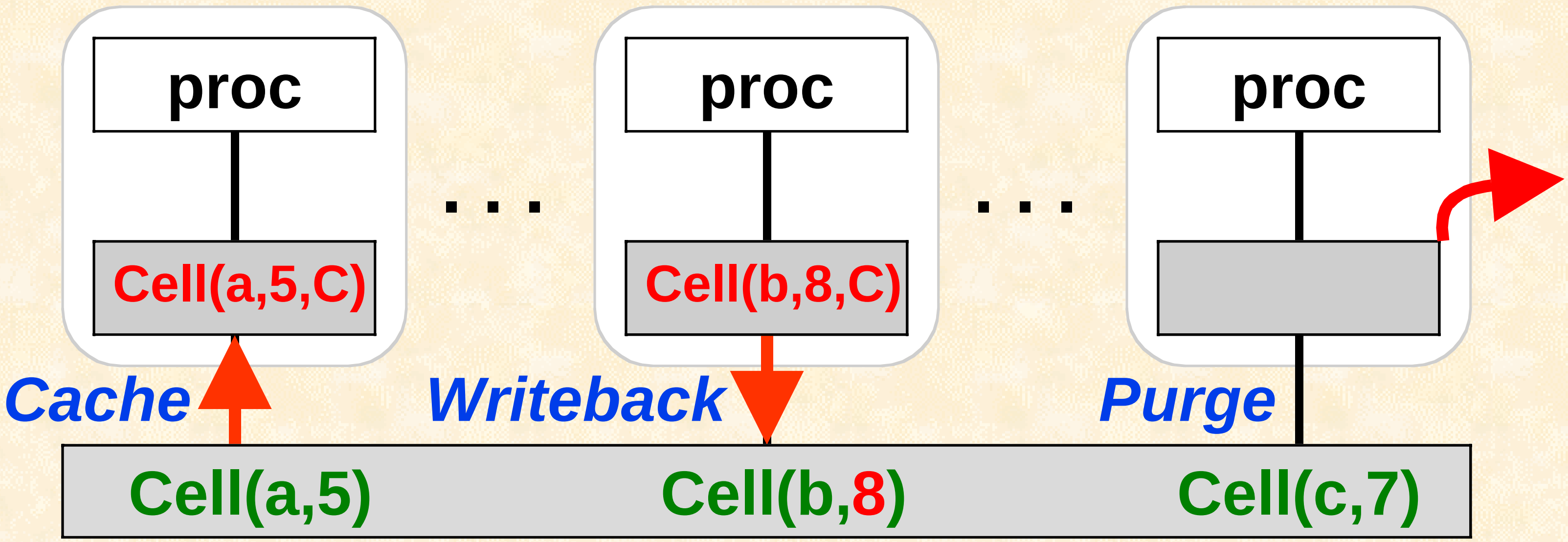
- LoadL reads from the cache if the address is cached
- StoreL writes into the cache and sets the state to Dirty

CRF: Commit and Reconcile



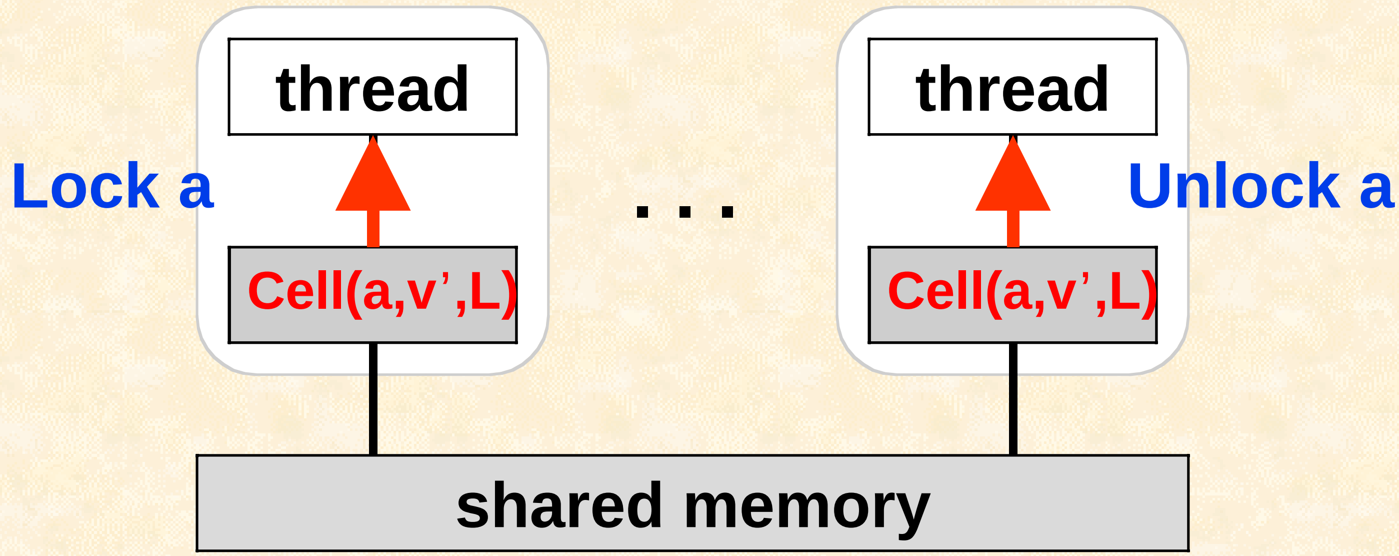
- Commit completes if the address is not cached in the Dirty state
- Reconcile completes if the address is not cached in Clean

CRF: Background Operations



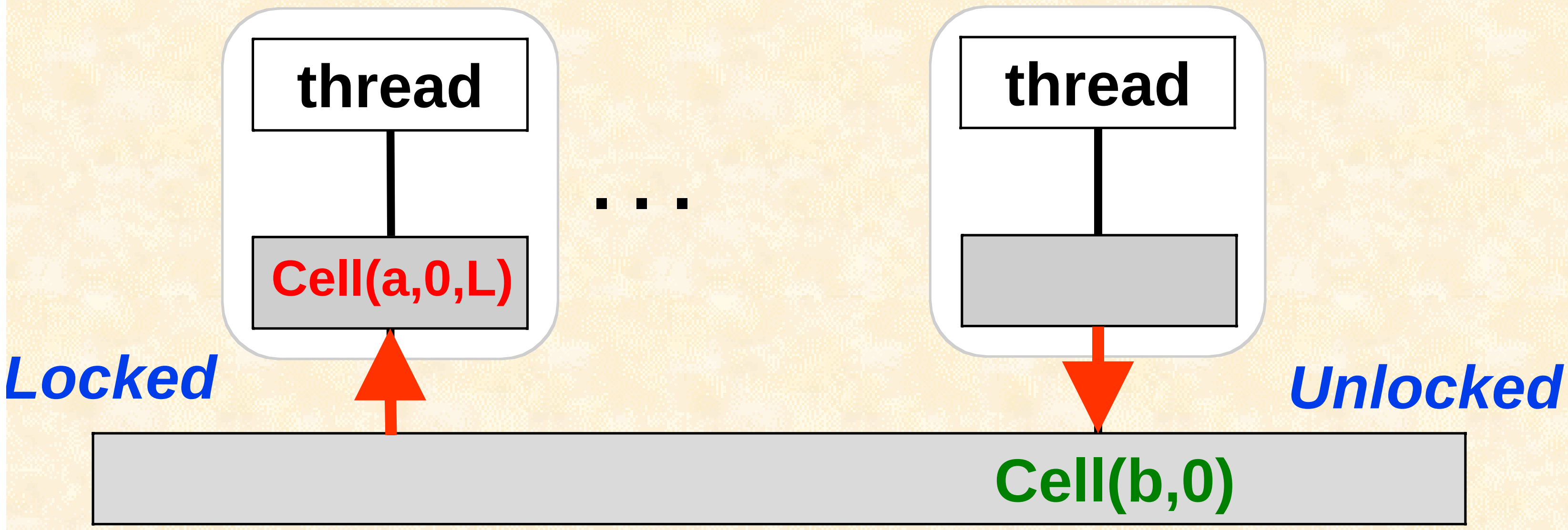
- **Cache (retrieve) a copy of an uncached address from memory**
- **Writeback a Dirty copy to memory and set its state Clean**
- **Purge a Clean copy**

CRF Extensions: Lock and Unlock



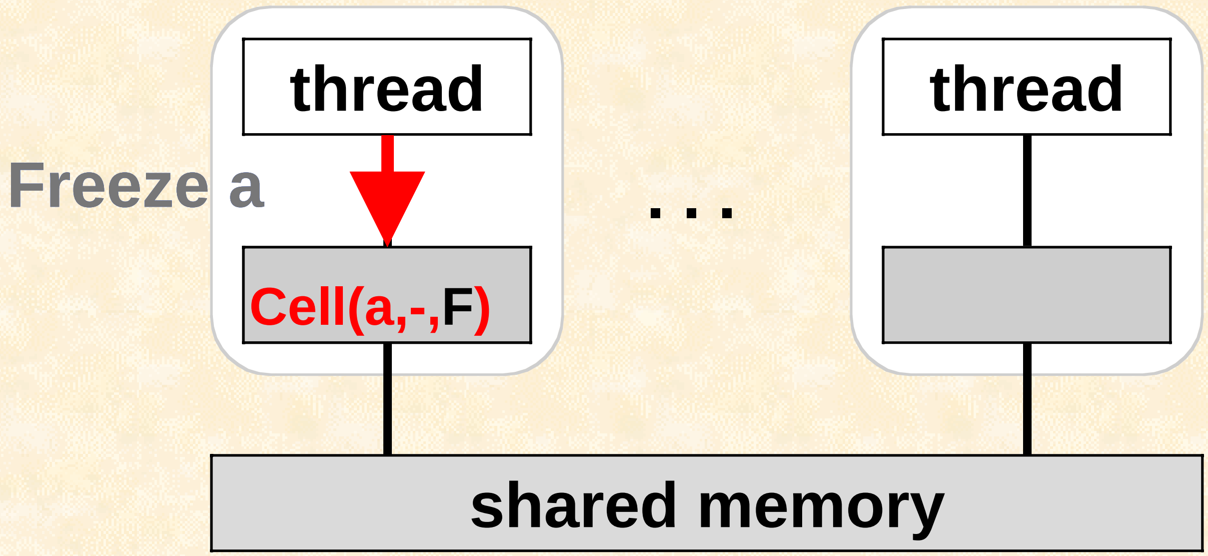
- Lock atomically increments the monitor count
- Unlock atomically decrements the monitor count

CRF: Background Locking



- Locked: retrieve an exclusive copy of an unheld monitor from memory
- Unlocked: return an unheld monitor to memory for others to use

CRF Extensions: Freeze



- Freeze changes cache state to Frozen
  - Reconcile can ignore Frozen entries