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**Motivation**

GC pauses are undesirable for modern enterprise
- Eliminate GC pauses from multi-threaded applications

**Mostly Concurrent GC**
- need barrier sync. for phase change

**On-The-Fly (OTF) GC**
- never stop more than one thread at a time

Challenge on OTF GC: designing correct and efficient write barrier

**Contributions**

1. Implemented Sapphire OTF GC on widely-used Java VM (Jikes RVM)
2. Developed general framework for OTF, parallel GC
3. Identified a pattern of lagged phase change and fixed a bug in Sapphire
4. Developed efficient concurrent copying method using transactions
5. Support subtleties such as `Object.hashCode()` and weak references

**1. Sapphire** [Hudson & Moss, 2001]

The only known on-the-fly copying GC, but no full-scale implementation exists

Replication: create semantically equivalent replica behind mutators

**Mark Phase**
- creates empty “shells”

**Copy Phase**
- copies object bodies

**Flip Phase**
- flips non-moving space

Mutator works with from-space and non-moving space

Mutator works with all spaces flip before writing from-space ptr

write barrier enforces invariant: no to-space → from-space pointer

**Sapphire’s bug**

Mutator A in copy phase
- INV: no non-moving → to-space

Mutator B in flip phase
- INV: no new non-moving → from-space

1. B stores pointer to to-space object X’ to non-moving space
2. A loads X’ from non-moving space
3. A stores pointer to from-space object Y to a slot of X’

We introduce intermediate states to prevent conflicts between invariants of adjacent phases

**2. Lagged Phase Change**

Different phases require different invariants

**Sapphire’s bug**

Mutator A in copy phase
- INV: no non-moving → to-space

Mutator B in flip phase
- INV: no new non-moving → from-space

1. B stores pointer to to-space object X’ to non-moving space
2. A loads X’ from non-moving space
3. A stores pointer to from-space object Y to a slot of X’

We introduce intermediate states to prevent conflicts between invariants of adjacent phases

**3. Concurrent Copy**

Sapphire: compare-and-swap per word

Our solution: copy-fence-verify per object

**Race detection**

- fewer synchronisation
- sequential memory access

Can use HW transaction for race detection
- transaction setup was heavier than fence
- similar throughput to SW transaction

**Evaluation Result**

- Long pauses were very rare (observed regardless of GC)
- Write barrier slowed down mutators to roughly half speed

- Normalised frequency
- Pause (ms)
- Distribution of times for time-critical task on dual Xeon E5520 @ 2.27GHz