ARTIST2 Summer School 2008 in Europe

Autrans (near Grenoble), France

September 8-12, 2008

Real-Time Programming in Java

Real-Time in the Age of Complex Systems

Invited Speaker: David F. Bacon

IBM Research

artist

Information Society Technologies

Classical Real-Time Control

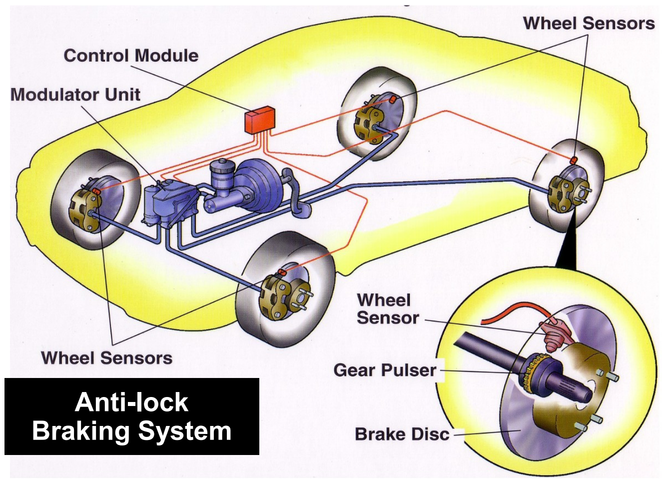
SENSE

↓

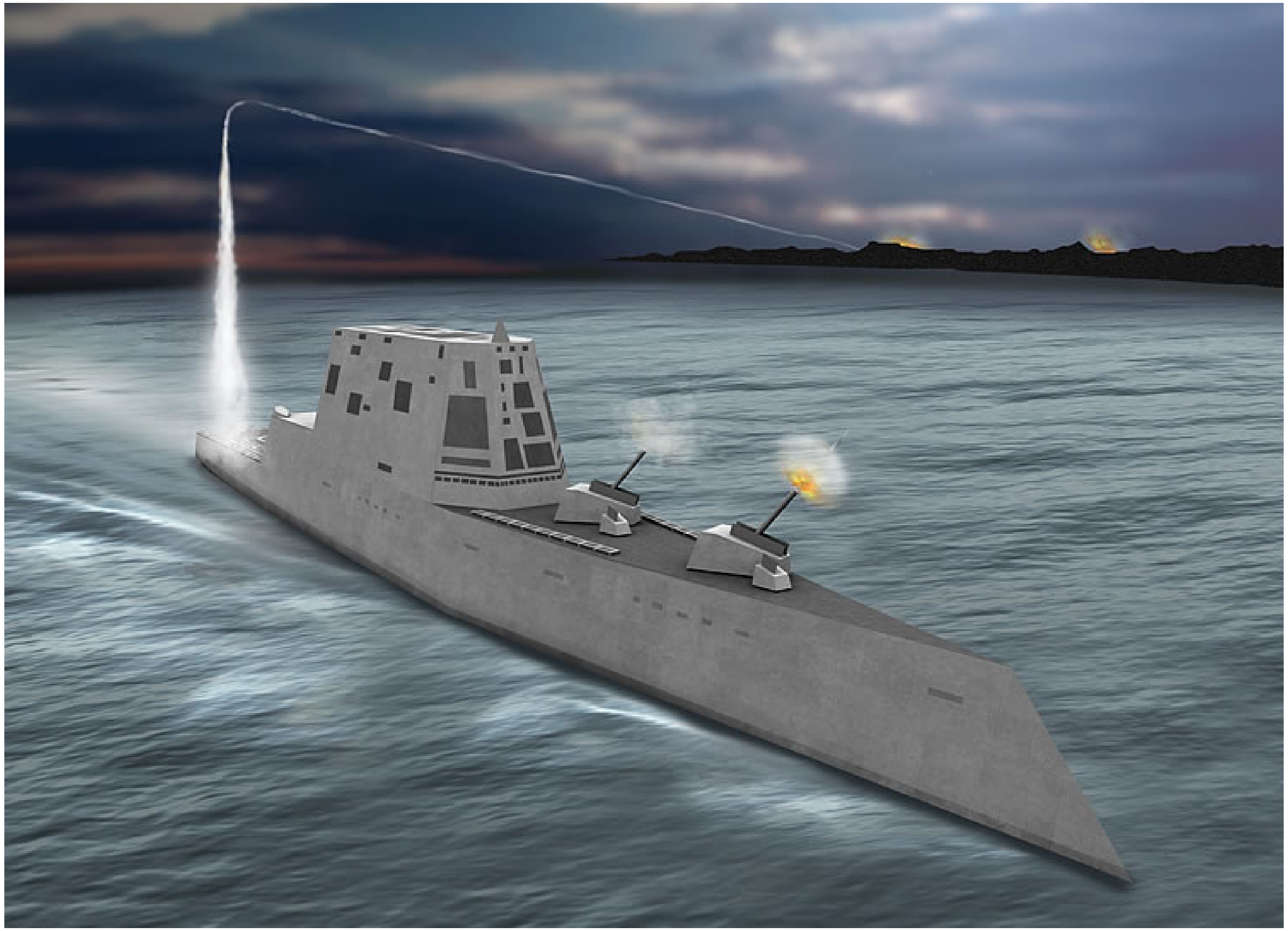
COMPUTE

↓

ACTUATE



Complex Real-Time Systems



What's Changing?

- Processing Power (instructions per 10ms)
  - 1970: 1K   Now: 40M   2020: 1G
- Ubiquitous Sensing and Actuation
  - e.g. video stream per cell phone
- More and more computing is real-time

Implications for Real-Time Systems

- Much Larger (in code and scope)
- Highly Dynamic
- Non-deterministic
  - non-determinism of underlying system desirable
- Different Kind of Software Engineering

Memory Management

STATIC

(arrays)

- Fortran
- Esterel
- Verilog

DYNAMIC

(malloc/free)

- C
- C++
- Ada
- Pascal

(new/garbage collect)

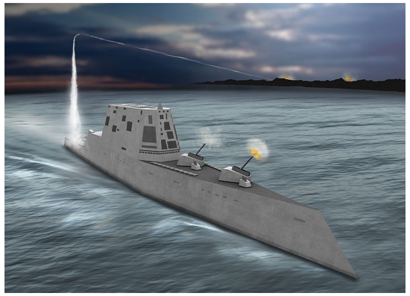
- Java
- Lisp
- C#
- Smalltalk

← Determinism Verifiability

Flexibility Software Engineering →

COMMITTED TO PRODUCTION

Telco SIP Switch



DDG-1000 Destroyer

Trade Execution

TARGETED

Playstation/Xbox etc

Automotive Electronics

RESEARCH

Java-based
Synthesizer

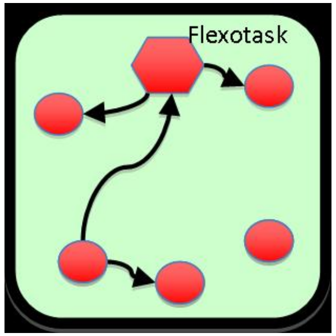
JAviator
(w/ Salzburg)

Air Java
(w/ Berkeley CE)

Three Approaches in Java

RTSJ Standard:
Scoped/Immortal Memory

Metronome:
Real-Time Garbage Collection



Flexotasks:
Time-Portable Java

Why is Real-Time Difficult in Java?

- No real-time scheduling APIs
- Garbage Collection
- Dynamic Class Loading
- Just-in-Time (JIT) Compilation
- Dynamic, average-case-based optimization

Real-Time Specification for Java

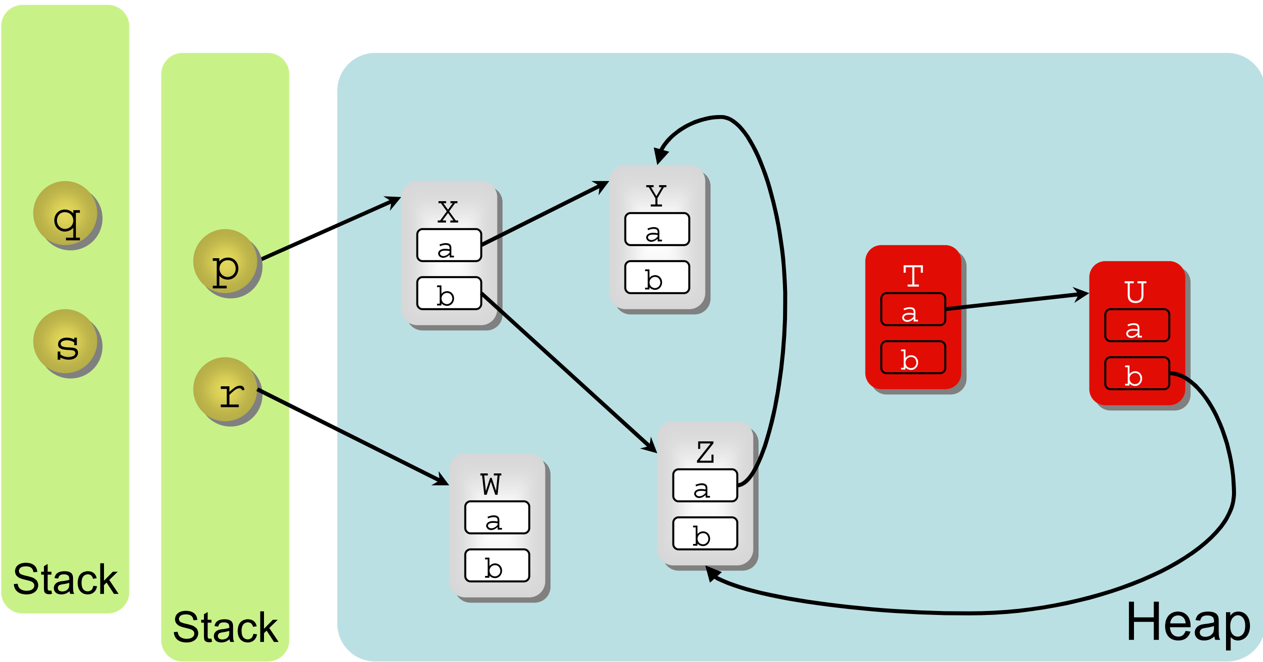
Two primary additions to the Java language:

– Real-Time Scheduling APIs

– Semi-manual memory management

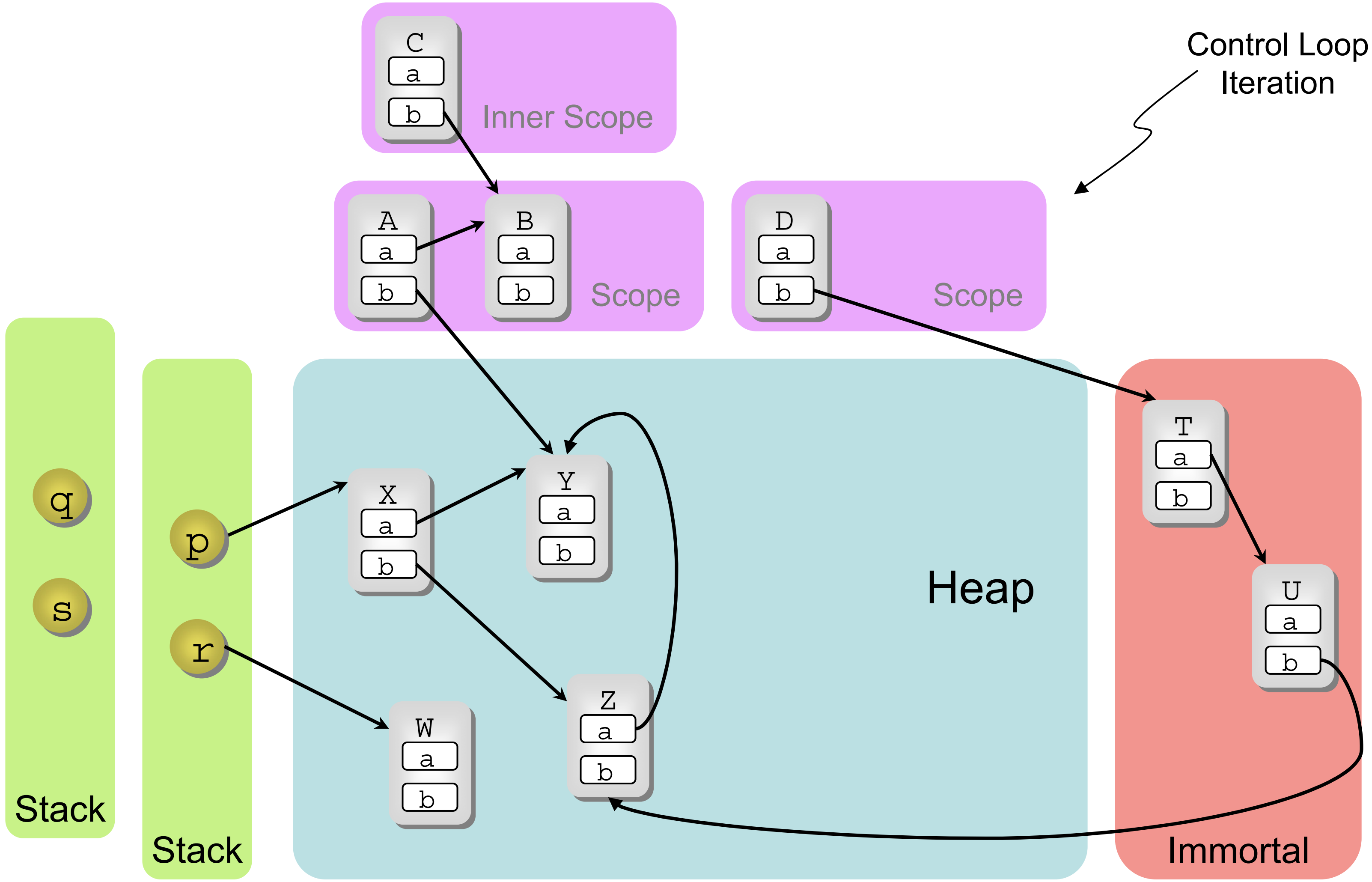
(real-time garbage collection “known” impossible)

Basic Java Memory Architecture

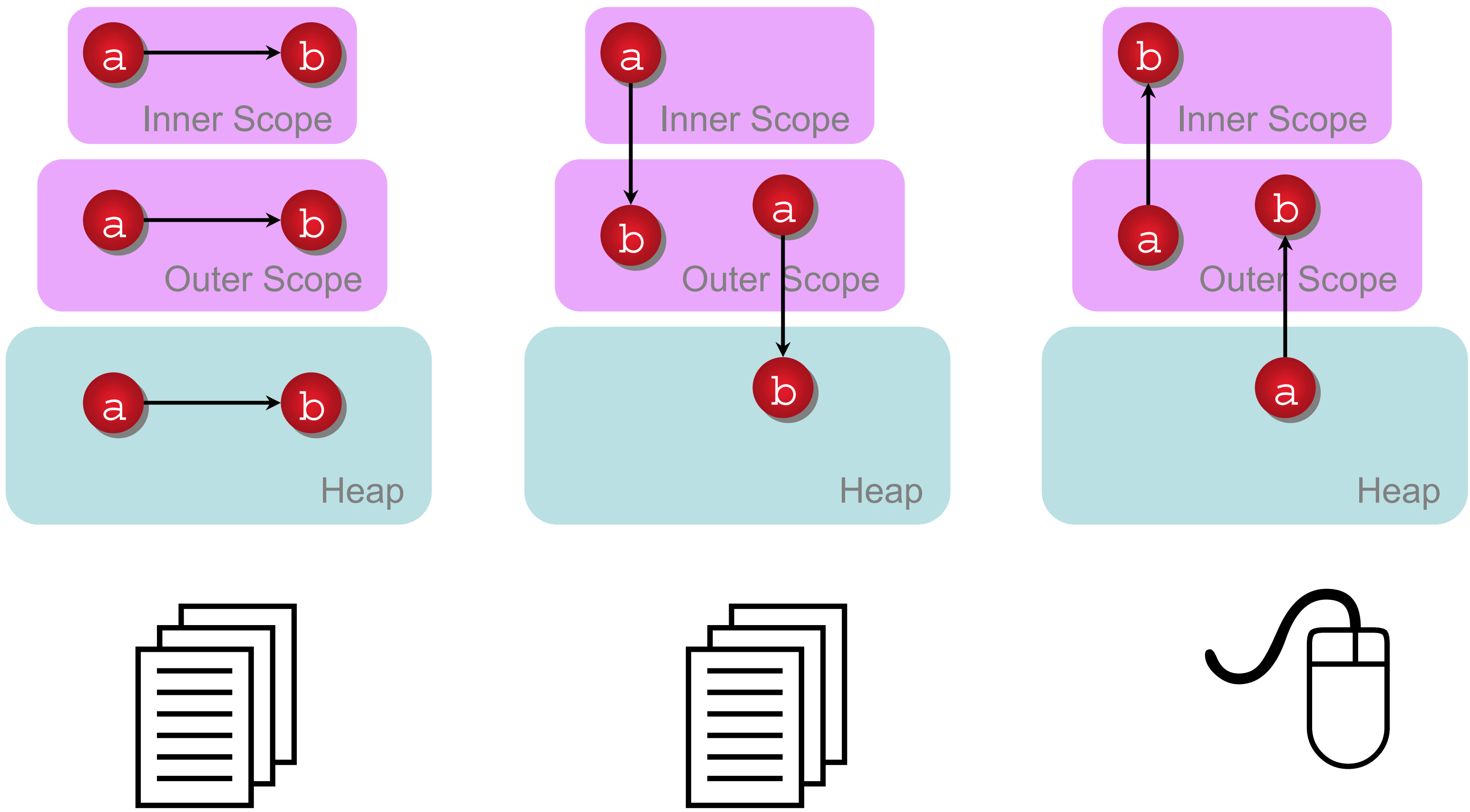



```
class Foo {
    Foo a;
    Foo b;
}
```

RTSJ Memory Architecture



```
f(a,b) { a.x = b; }
```



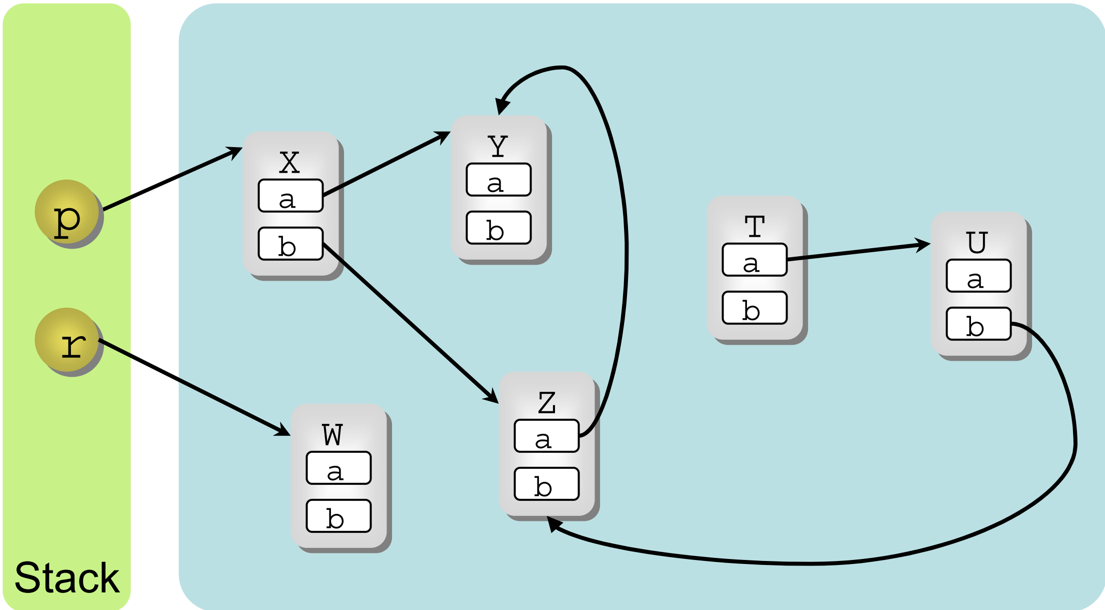
a
b
Inner Scope
a
b
Outer Scope
a
b
Heap
a
Inner Scope
b
a
Outer Scope
b
Heap
b
Inner Scope
a
b
Outer Scope
a
Heap

RTSJ Memory Management Issues

- Complex Programming Model
- Non-compositional
- Run-time Failures
- Checking Overhead
- Storage Leaks in Immortal Memory
- Often Poorly Suited (e.g. Producer/Consumer)

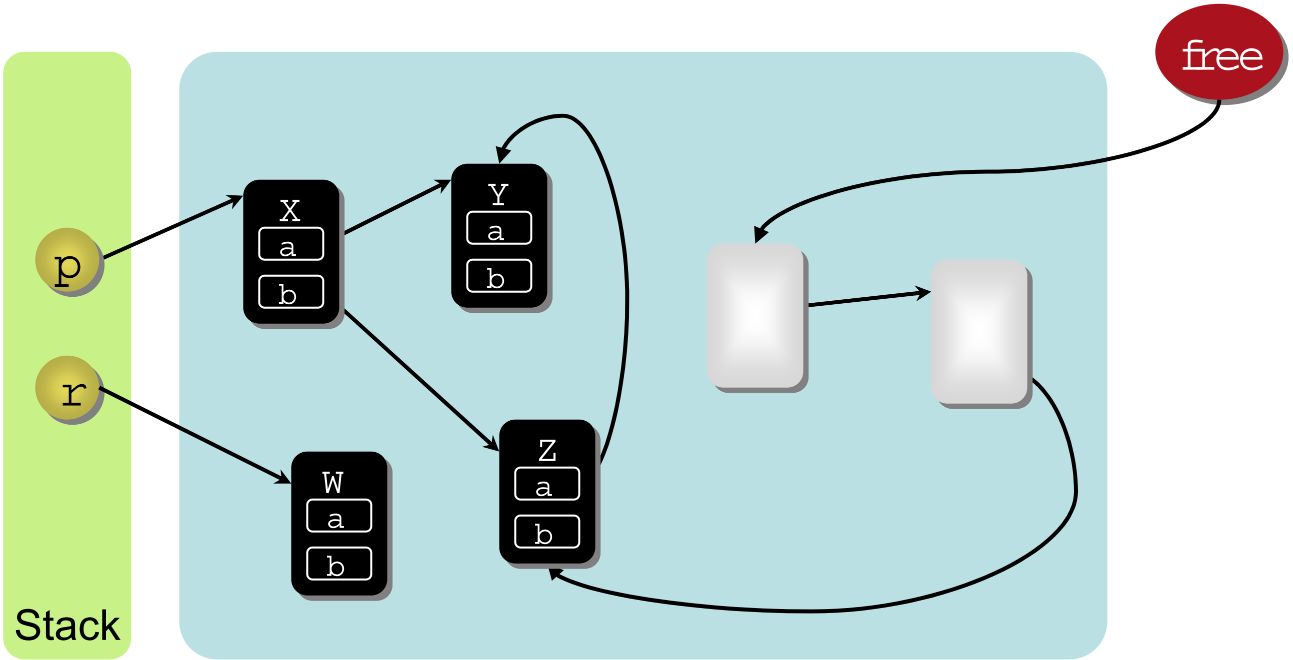
Metronome:
Real-Time Garbage Collection

GC: A Simple Problem (?)



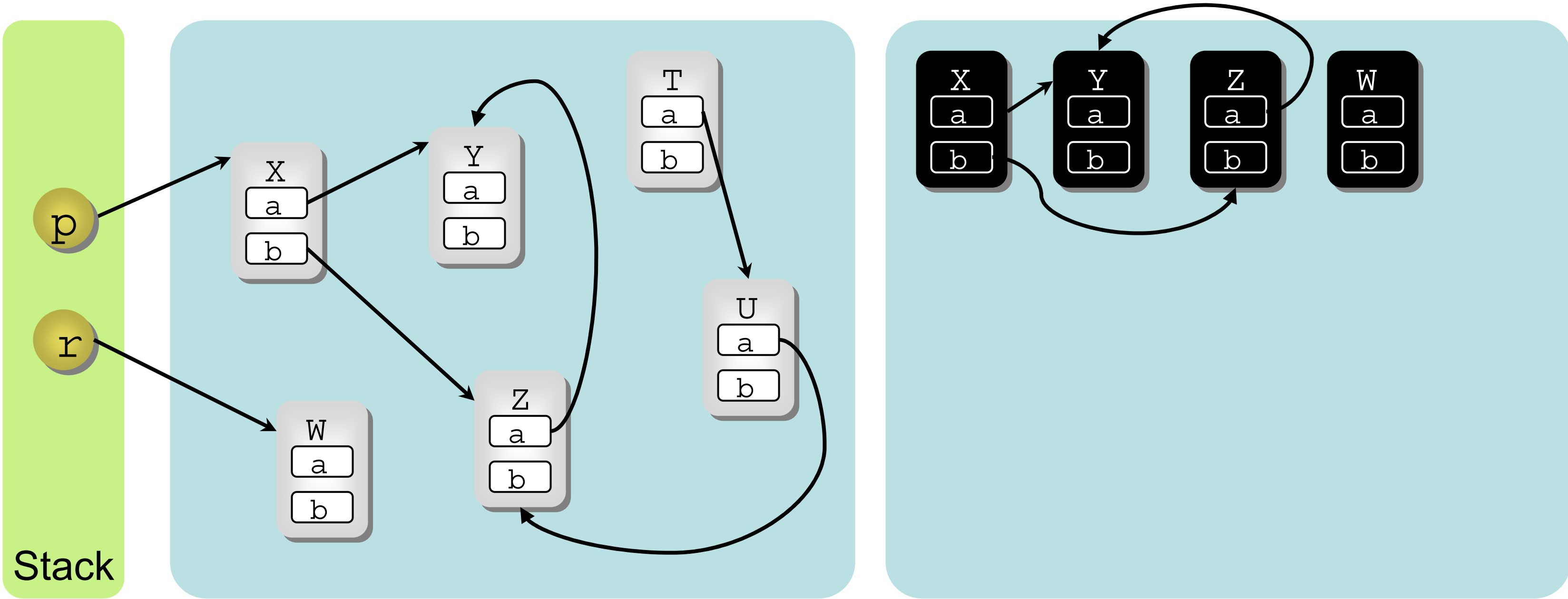
- Transitive Graph Closure
- Application is Stopped During Collection
- Memory is only freed at the end

Basic Approaches: Mark/Sweep



- *O(live)* mark phase but *O(heapsize)* sweep
- Usually requires no copying
- Mark stack is *O(maxdepth)*

Basics II: Semi-space Copying



- *O(live)*
- If single-threaded, no mark stack needed
- Wastes 50% of memory

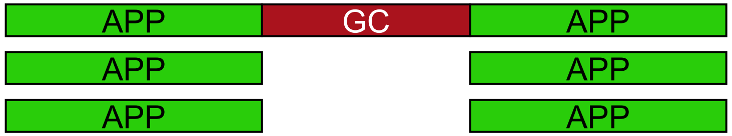
Demo: Synthesizer in Java

- Human performance:
  - Latency < 8ms end-to-end
  - Jitter < 10us

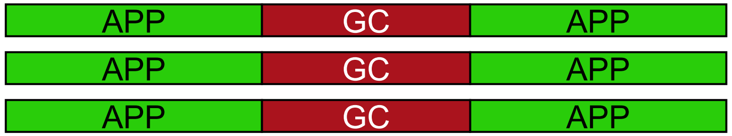
- MIDI/soundcard latency: 2.5ms

Kinds of “Concurrent” Collection

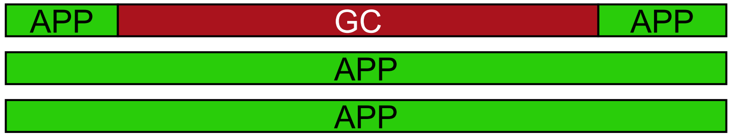
- “Stop the World”



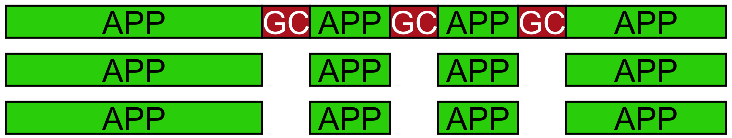
- Parallel



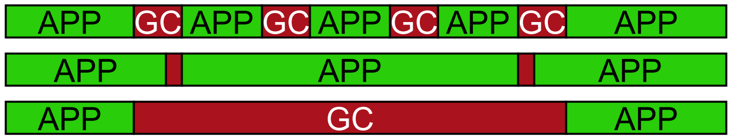
- Concurrent



- Incremental



Our Subject: Metronome-2 System

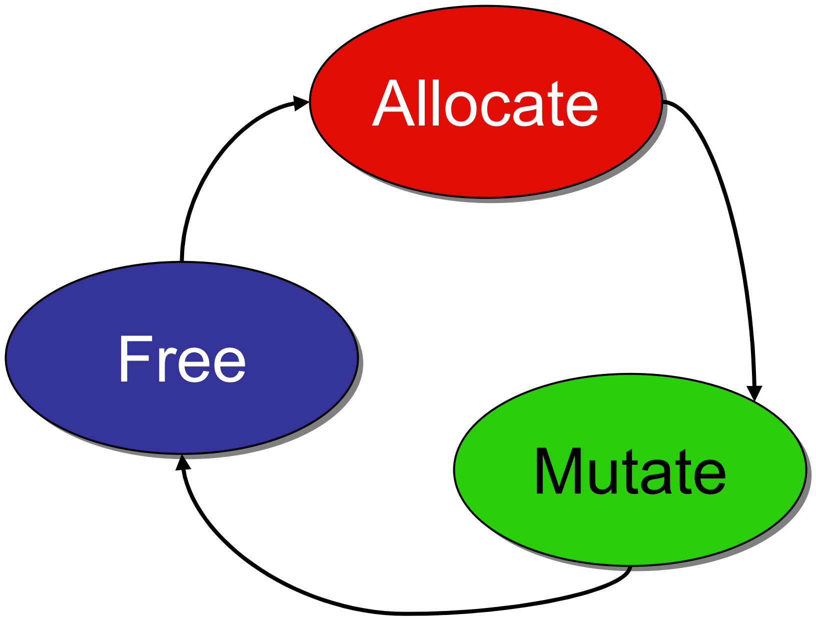


- Parallel, Incremental, and Concurrent
- No increment exceeds 450us
- Real-time Scheduling
- Smooth adaptation from under- to over-load
- Implementation in production JVM

What Does “Real-time” Mean?

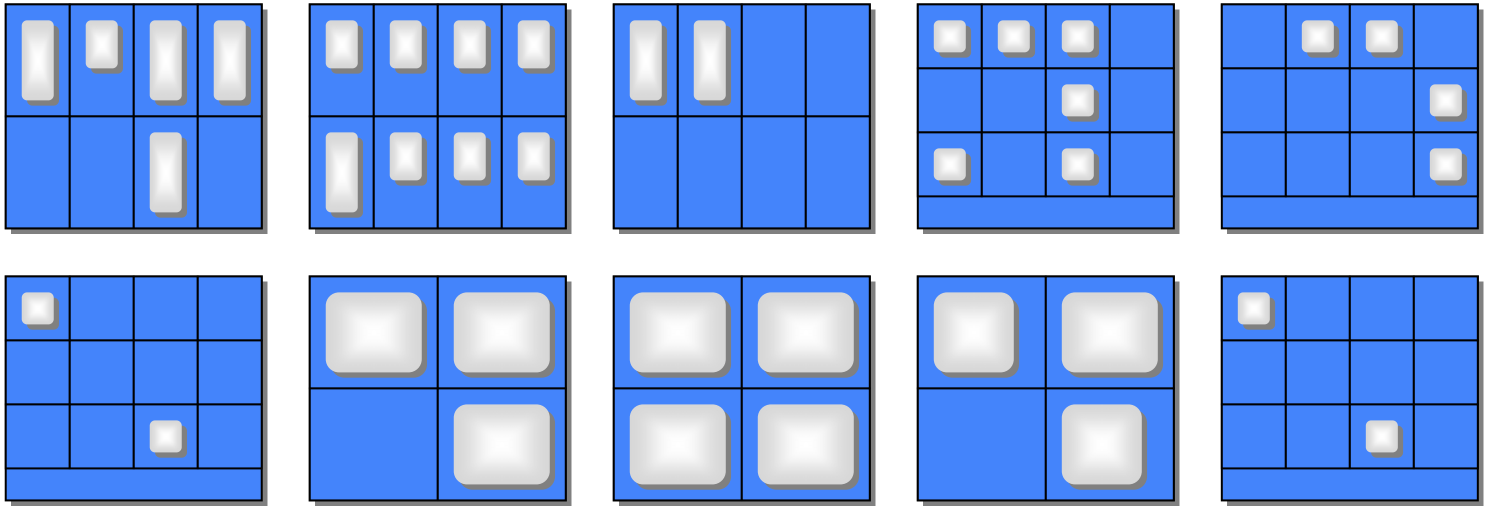
- Minimal, predictable interruption of application
- Collection finishes before heap is exhausted
- “Real space” - bounded, predictable memory
- Honor thread priorities

The Cycle of Life



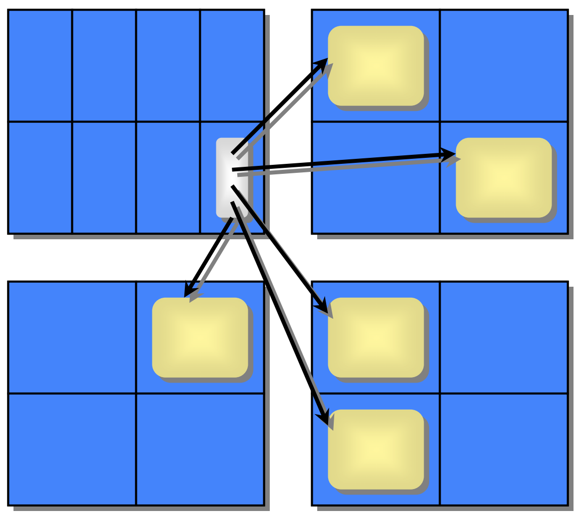
- Not really a “garbage collector”…
- … but a memory management subsystem

Metronome Memory Organization



- Page-based
- Segregated free lists
- Ratio bounds internal & page-internal fragmentation

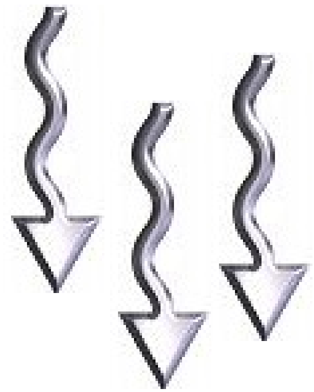
Large Objects: Arraylets



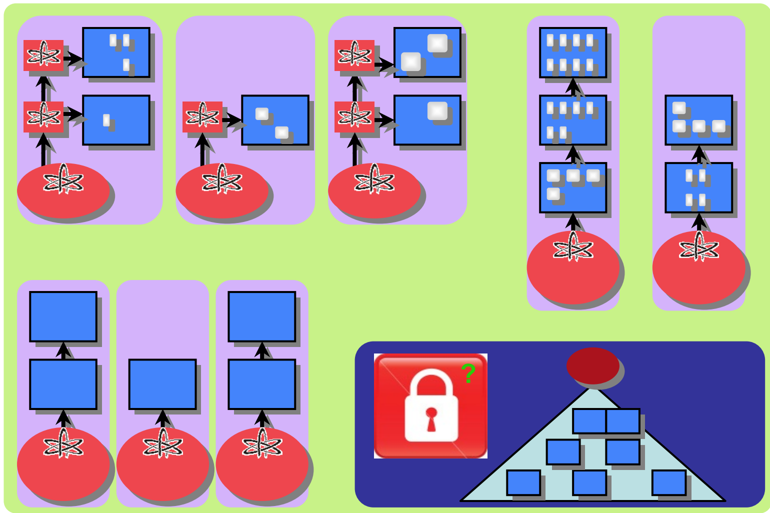
- (Almost) eliminates external fragmentation
- (Almost) eliminates need for compaction
- Very large arrays still need contiguous pages
- Extra indirection for array access

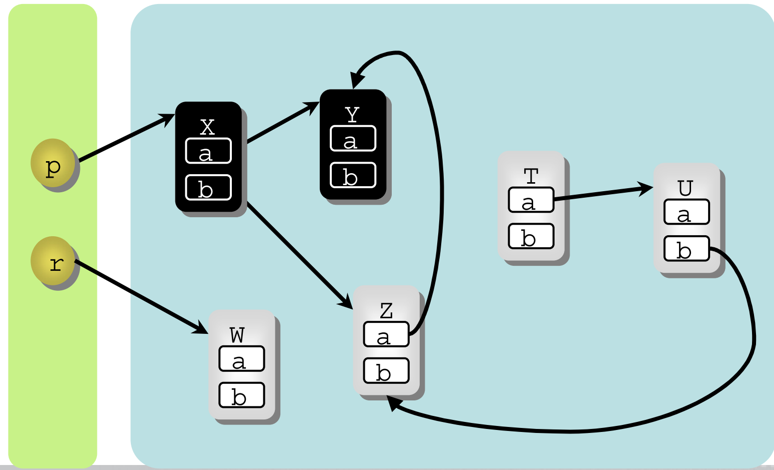
Handling the Concurrency

GC
Threads

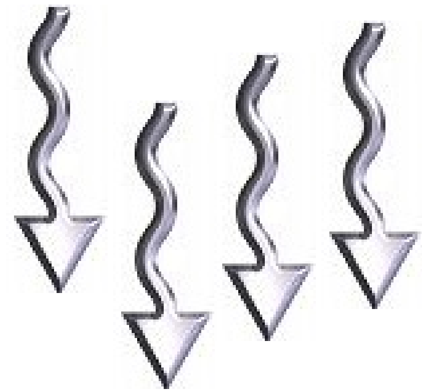


- Mark
- Collect
- Format





Application
("mutator")
Threads



- Load pointer
- Store pointer
- Allocate

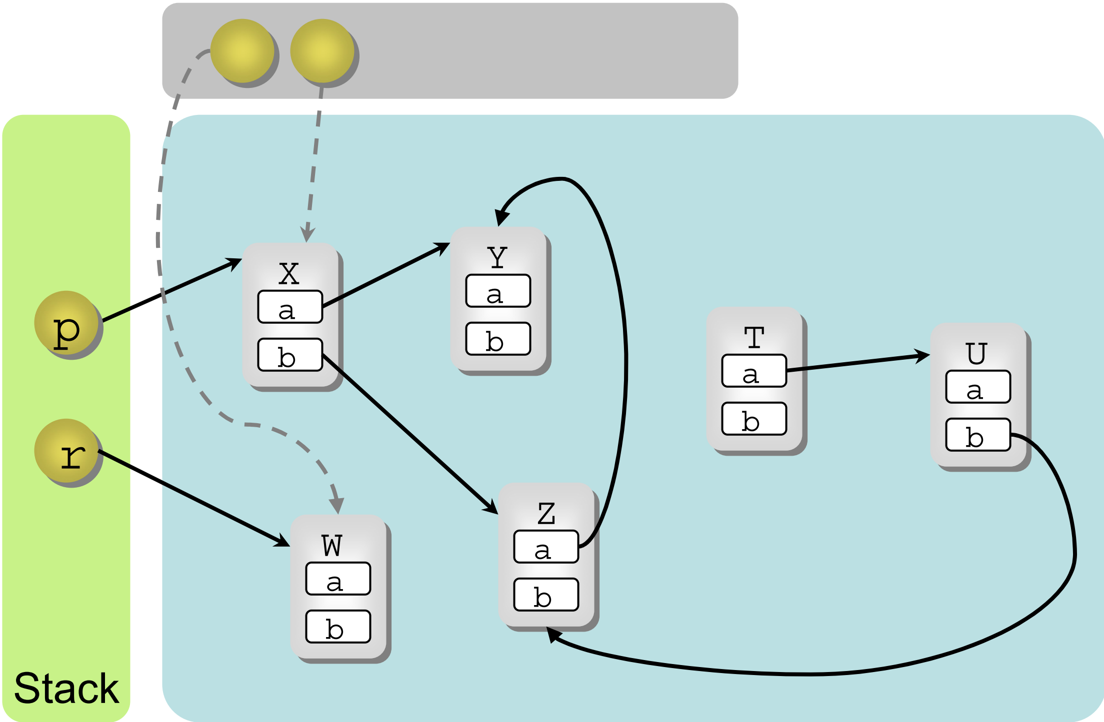
Yuasa Snapshot Algorithm (1990)

- Logically
  - Take a “copy-on-write” heap snapshot
  - Collect the garbage in that snapshot

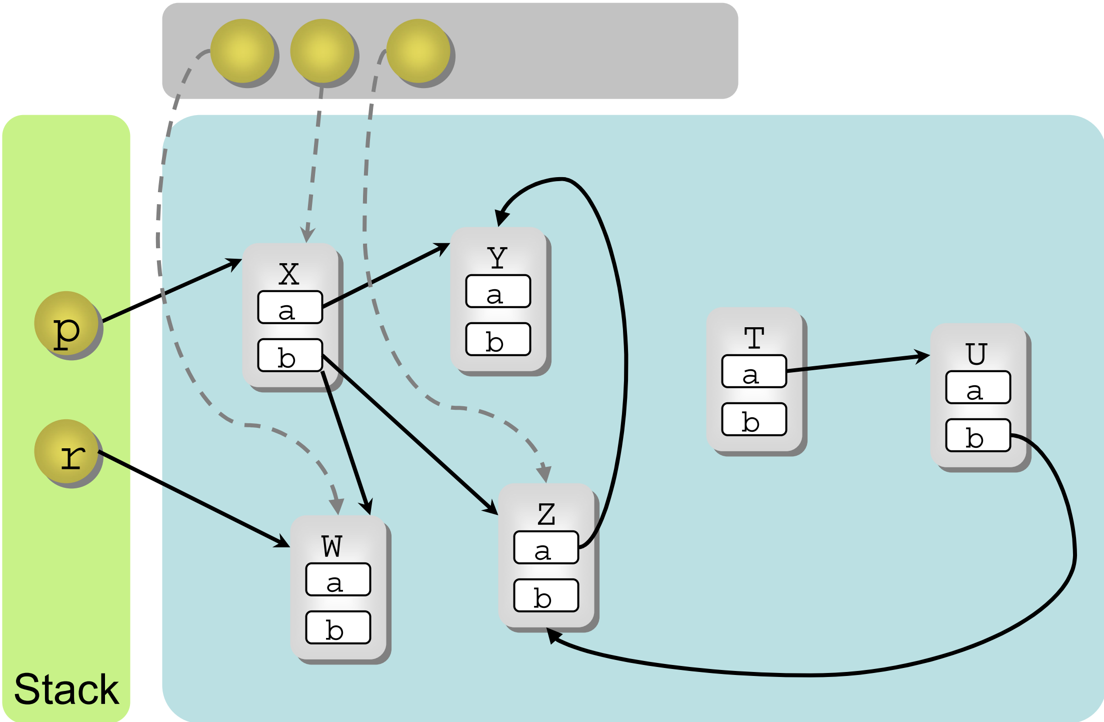
- Physically
  - Stop all threads
  - Copy their stacks (“roots”)
  - Force them to save over-written pointers
  - Trace roots and over-written pointers

* Dijktstra’75, Steele’76

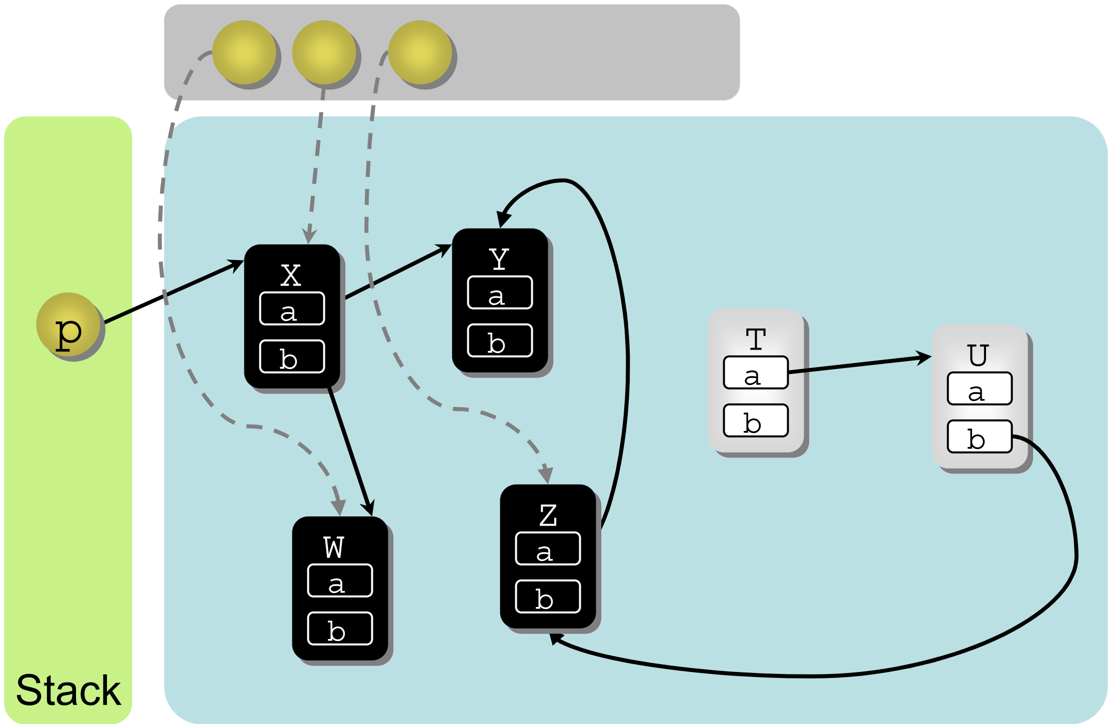
1: Take Logical Snapshot



2(a): Copy Over-written Pointers

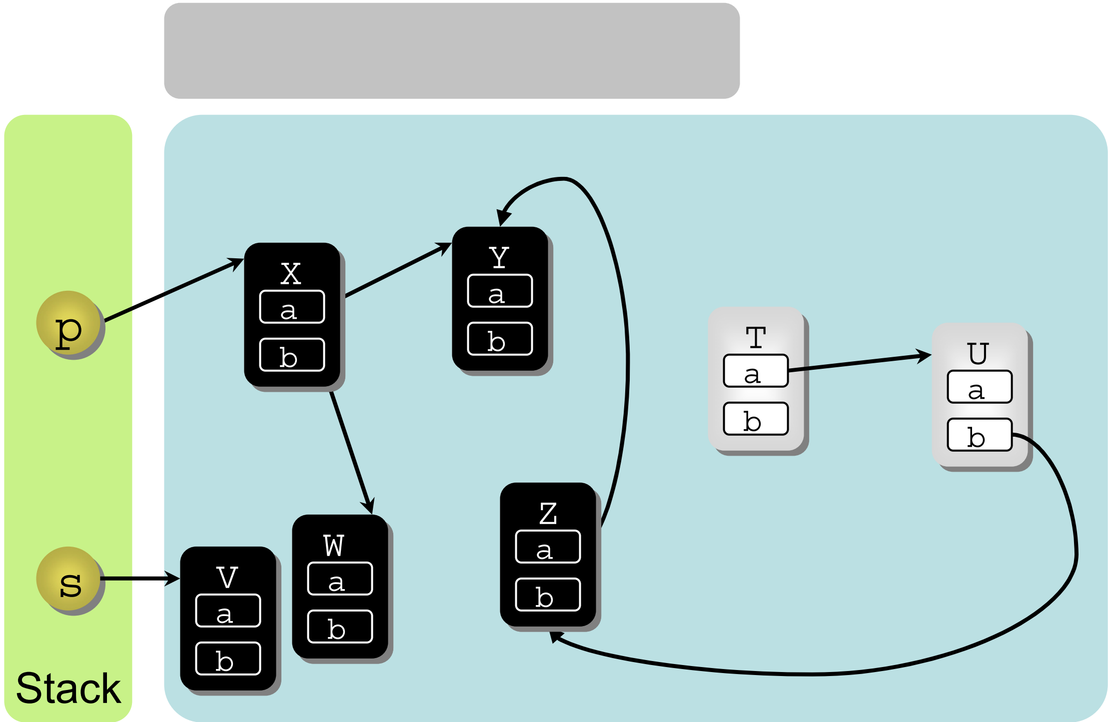


2(b): Trace

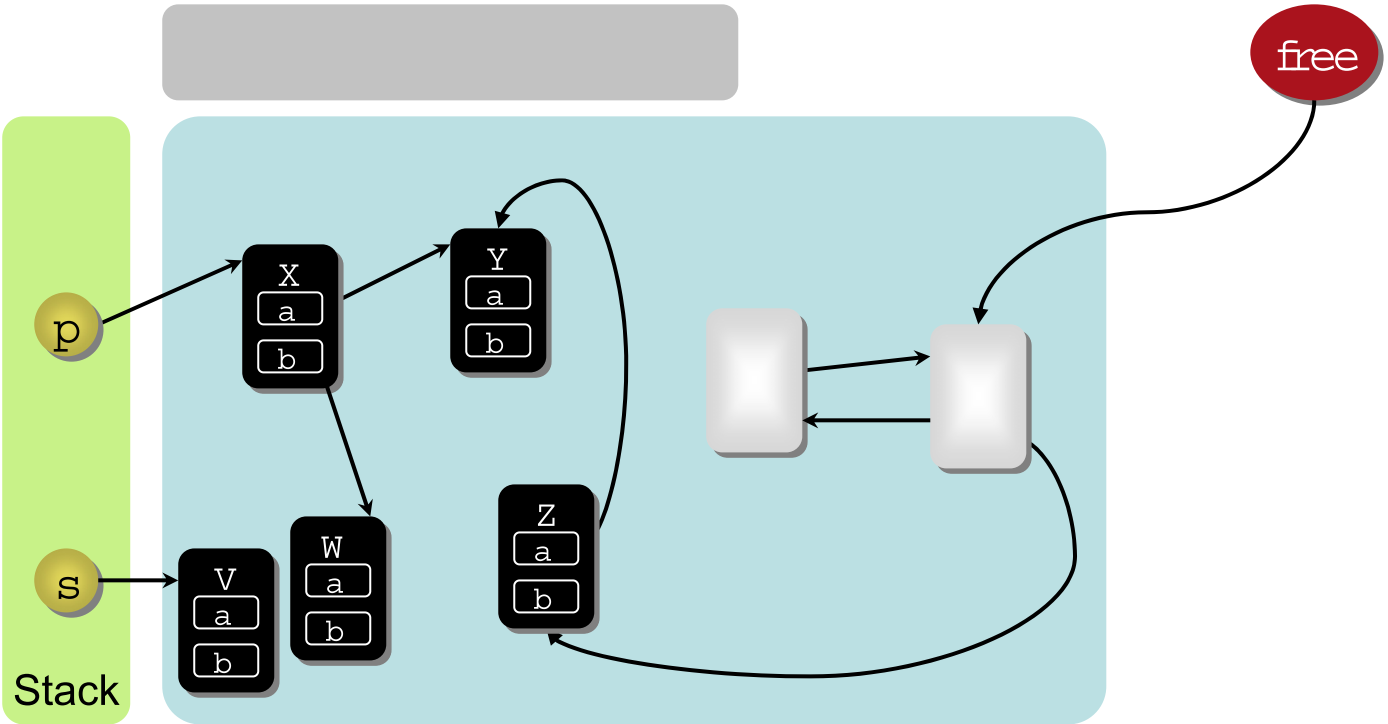


* Color is per-object mark bit

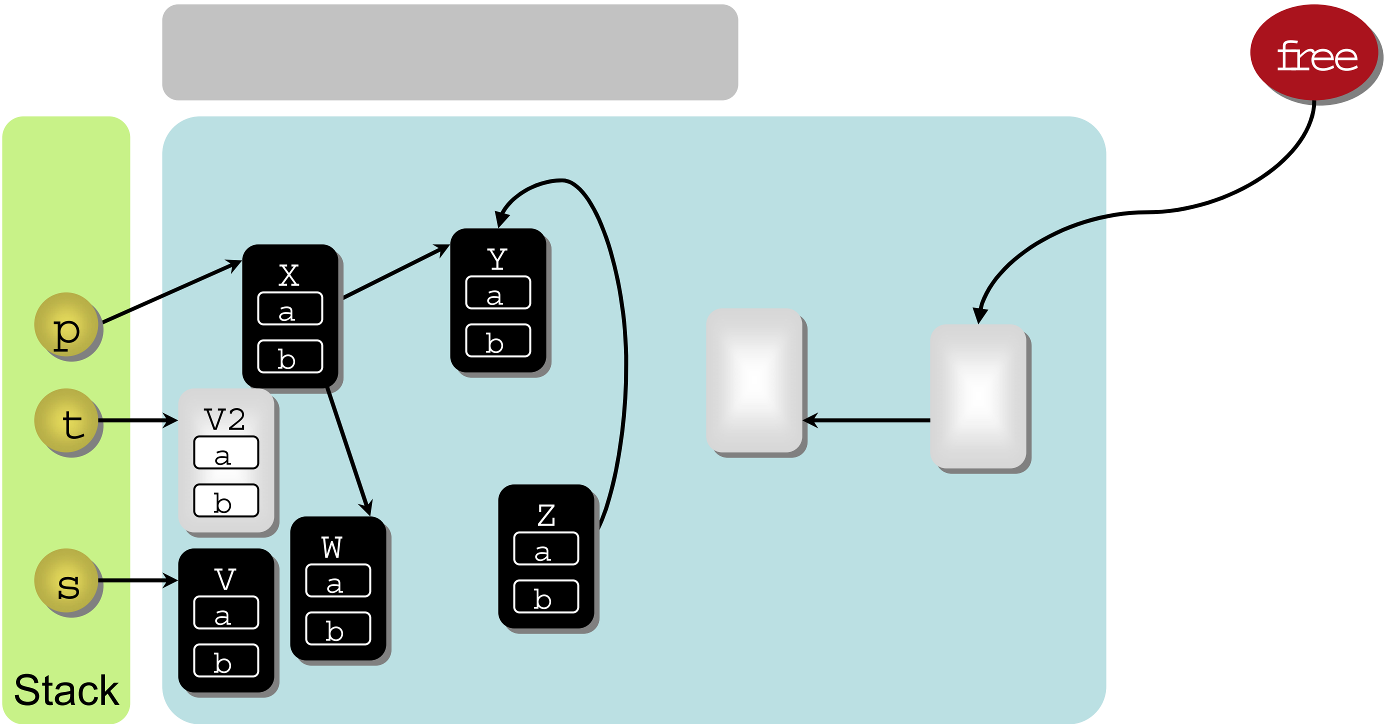
2(c): Allocate “Black”



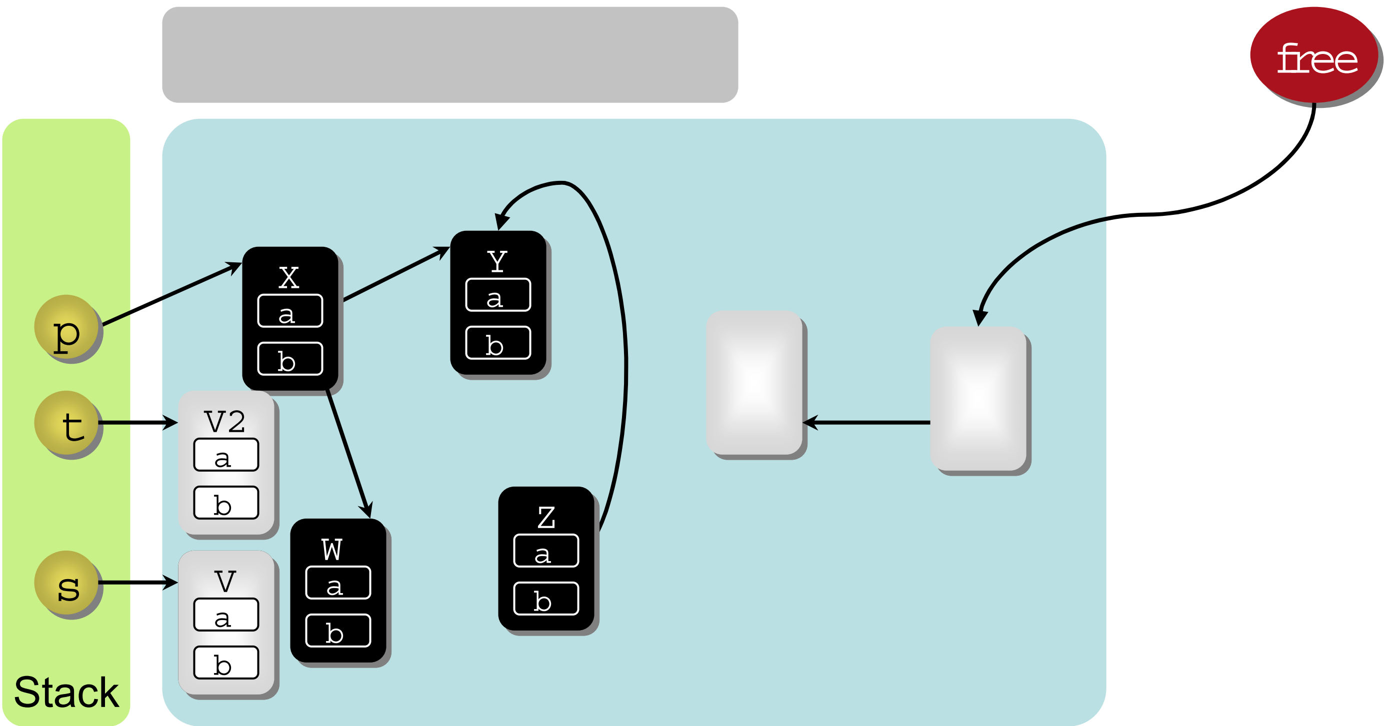
3(a): Sweep Garbage



3(b): Allocate “White”



4: Clear Marks



Yuasa Algorithm Phases

- Snapshot stack and global roots
- Trace
- Flip
- Sweep
- Flip
- Clear Marks

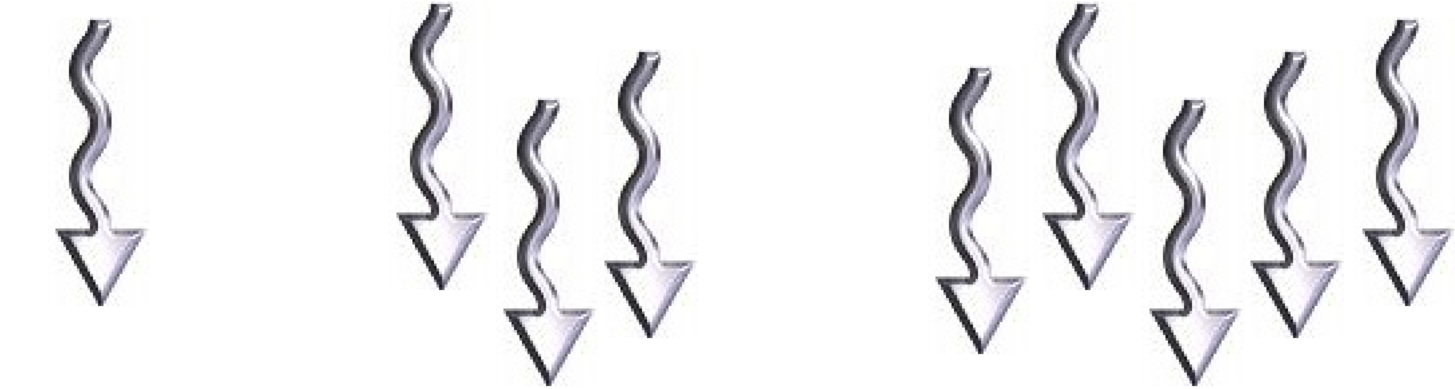
* Synchronous

Metronome-2 Concurrency

GC Master Thread

GC Worker Threads

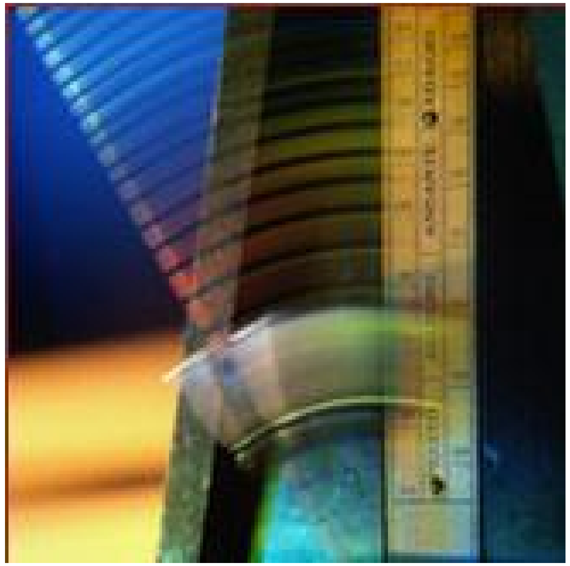
Application Threads (may do GC work)

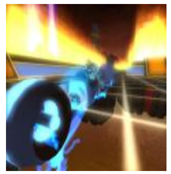


Metronome-2 Phases

- Initiation
  - Setup
    - turn double barrier on
- Root Scan
  - Active Finalizer scan
  - Class scan
  - **Thread scan****
    - switch to single barrier, color to black
  - Debugger, JNI, Class Loader scan
- Trace
  - **Trace***
  - **Trace Terminate*****
- Re-materialization 1
  - Weak/Soft/Phantom Reference List Transfer
  - **Weak Reference clearing**** (snapshot)
- Re-Trace 1
  - Trace Master
  - **(Trace*)**
  - **(Trace Terminate***)**
- Re-materialization 2
  - Finalizable Processing
- Clearing
  - Monitor Table clearing
  - JNI Weak Global clearing
  - Debugger Reference clearing
  - JVMTI Table clearing
  - Phantom Reference clearing
- Re-Trace 2
  - Trace Master
  - **(Trace*)**
  - **(Trace Terminate***)**
  - Class Unloading
- Flip
  - **Move Available Lists to Full List*** (contention)
    - turn write barrier off
  - **Flush Per-thread Allocation Pages****
    - switch allocation color to white
    - switch to temp full list
- Sweeping
  - **Sweep***
  - **Switch to regular Full List****
  - **Move Temp Full List to regular Full List*** (contention)
- Completion
  - Finalizer Wakeup
  - Class Unloading Flush
  - **Clearable Compaction****
  - Book-keeping

*** Parallel**
**** Callback**
***** Single actor symmetric**





http://www.research.ibm.com/metronome

https://sourceforge.net/projects/tuningforkvp