A JVM Does That???

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A JVM Does That???

- Been a JVM Engineer for over a decade
- I'm still amazed at what goes in a JVM
- Services have increased over time
- Many new services painfully "volunteered" by naive change in specs

Some JVM Services

- High Quality GC
  - Parallel, Concurrent, Collection
  - Low total allocation cost
- High Quality Machine Code Generation
  - Two JITs, JIT'd Code Management, Profiling
  - Bytecode cost model
- Uniform Threading & Memory Model
  - Locks (synchronization), volatile, wait, notify
- Type Safety

Some JVM Services

- Dynamic Code Loading
  - Class loading, Deoptimization, re-JIT'ing
- Quick high-quality Time Access
  - System.currentTimeMillis
- Internal introspection services
  - Reflection, JNI, JVMTI, JVMDI/JVMPI, Agents
- Access to huge pre-built library
- Access to OS
  - threads, scheduling, priorities, native code

Too Many Services?

- Where did all this come from?
- Mostly incrementally added over time
- The Language, JVM, & Hardware all co-evolved
  - e.g. incremental addition of finalizers, JMM, 64-bits
  - Support for high core-count machines

Why Did We Add All These Services?

- Because Illusions Are Powerful Abstractions

The 'V' in JVM

- "Virtual" – Its a Great Abstraction
- Programmers focus on value-add elsewhere
- JVM Provides Services
- The selection of Services is ad-hoc
  - Grown over time as needed
  - Some services are unique to Java or the JVM
  - Many services overlap with existing OS services
    - But sometimes have different requirements

Agenda

- Introduction (just did that)
- **Illusions We Have**
- Illusions We Think We Have or Wish We Had
- Sorting Our Illusions Out

Illusion: Infinite Memory

- Garbage Collection – The Infinite Heap Illusion
  - Just allocate memory via 'new'
  - Do not track lifetime, do not 'free'
  - GC figures out What's Alive and What's Dead
- Vastly easier to use than malloc/free
  - Fewer bugs, quicker time-to-market
- Enables certain kinds of concurrent algorithms
  - Just too hard to track liveness otherwise

Illusion: Infinite Memory

- GC have made huge strides in the last decade
  - Production-ready robust, parallel, concurrent
  - Still major user pain-point
    - Too many tuning flags, GC pauses, etc
  - Major Vendor point of differentiation, active dev
  - Throughput varies by maybe 30%
  - Pause-times vary over 6 orders of magnitude
    - (Azul GPGC: 100's of Gig's w/10msec)
    - (Stock full GC pause: 10's of Gig's w/10sec)
    - (IBM Metronome: 100's Megs w/10microsec)

Illusion: Bytecodes Are Fast

- Class files are a lousy way to describe programs
- There are better ways to describe semantics than Java bytecodes
  - But we're stuck with them for now
  - Main win: hides CPU details
- Programmers rely on them being "fast"
- It's a big Illusion: Interpretation is slow
- JIT'ing brings back the "expected" cost model

Illusion: Bytecodes Are Fast

- JVMs eventually JIT bytecodes
  - To make them fast!
  - Some JITs are high quality optimizing compilers
    - Amazingly complex beasties in their own rights
  - i.e. JVMs bring "gcc -O2" to the masses
- But cannot use "gcc"-style compilers directly:
  - Tracking OOPs (ptrs) for GC
  - Java Memory Model (volatile reordering & fences)
  - New code patterns to optimize

Illusion: Bytecodes Are Fast

- JIT'ing requires Profiling
  - Because you don't want to JIT everything
- Profiling allows focused code-gen
- Profiling allows better code-gen
  - Inline whats hot
  - Loop unrolling, range-check elimination, etc
  - Branch prediction, spill-code-gen, scheduling
- JVMs bring Profiled code to the masses!

Illusion: virtual calls are fast

- C++ avoids virtual calls – because they are slow
- Java embraces them – and makes them fast
  - Well, mostly fast – JIT's do Class Hierarchy Analysis
  - CHA turns most virtual calls into static calls
  - JVM detects new classes loaded, adjusts CHA
    - May need to re-JIT
  - When CHA fails to make the call static, *inline caches*
  - When IC's fail, virtual calls are back to being slow

Illusion: Partial Programs Are Fast

- JVMs allow late class loading, name binding
  - i.e. classForName
- Partial programs are as fast as whole programs
  - Adding new parts in (e.g. Class loading) is "cheap"
  - May require: deoptimization, re-profiling, re-JIT
  - Deoptimzation is a hard problem also

Illusion: Consistent Memory Models

- ALL machines have different memory models
  - The rules on visibility vary widely from machines
  - And even within generations of the same machine
  - X86 is very conservative, so is Sparc
  - Power, MIPS less so
  - IA64 & Azul very aggressive
- Program semantics depend on the JMM
  - So must match the JMM
  - Else *program meaning* would depend on hardware!

Illusion: Consistent Memory Models

- Very different hardware memory models
- None match the Java Memory Model
- The JVM bridges the gap -
  - While keeping normal loads & stores fast
  - Via combinations of fences, code scheduling, placement of locks & CAS ops
  - Requires close cooperation from the JITs
  - Requires detailed hardware knowledge

Illusion: Consistent Thread Models

- Very different OS thread models
  - Linux, Solaris, AIX
  - But also cell phones, iPad, etc
- Java just does 'new Thread'
  - On micro devices to 1000-cpu giant machines
  - and *synchronized*, *wait, notify, join,* etc, all just work

Illusion: Locks are Fast

- Contended locks obviously block and must involve the OS
  - (Expect fairness from the OS)
- Uncontended locks are a dozen nano's or so
  - Biased locking: ~2-4 clocks (when it works)
  - *Very* fast user-mode locks otherwise
- Highly optimized because *synchronized* is so common

Illusion: Locks are Fast

- People don't know how to program concurrently
  - The 'just add locks until it works' mentality
  - i.e. Lowest-common-denominator programming
  - So locks became common
  - So JVMs optimized them
- This enabled a particular concurrent programming style
- And we, as an industry, learned alot about concurrent programming as a result

Illusion: Quick Time Access

- System.currentTimeMillis
  - Called *billions* of times/sec in some benchmarks
  - Fairly common in all large java apps
  - Real Java programs expect that:
    if T1's Sys.cTM < T2's Sys.cTM
    then T1 <<<*happens_before* T2
- But cannot use, e.g. X86's "tsc" register
  - Value not coherent across CPUs
  - Not consistent, e.g. slow ticking in low-power mode
  - Monotonic per CPU – but not per-thread

Illusion: Quick Time Access

- System.currentTimeMillis
  - Switching from fastest linux gettimeofday call
    - (mostly-user-mode atomic time struct read)
    - gettimeofday gives *quality* time
  - To a plain *load* (updated by background thread)
  - Was worth 10% speed boost on key benchmark
- Hypervisors like to "idealize" tsc :
  - Means: uniform monotonic ticking
  - Means: slows access to tsc by 100x?

Agenda

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- Illusions We Have
- **Illusions We Think We Have or Wish We Had**
- Sorting Our Illusions Out

Illusions We'd Like To Have

- Infinite Stack
  - e.g. Tail calls. Useful in some functional languages
- Running-code-is-data
  - e.g. Closures
- 'Integer' is as cheap as 'int'
  - e.g. Auto-boxing optimizations
- 'BigInteger' is as cheap as 'int'
  - e.g. Tagged integer math, silent overflow to infinite precision integers

Illusions We'd Like To Have

- Atomic Multi-Address Update
  - e.g. Software Transactional Memory
- Fast alternative call bindings
  - e.g. invokedynamic

Illusions We Think We Have

- This mass of code is maintainable:
  - HotSpot is approaching 15yrs old
  - Large chunks of code are fragile
    - (or very 'fluffy' per line of code)
  - Very slow new-feature rate-of-change
- Azul Systems has been busy rewriting lots of it
  - Many major subsystems are simpler, faster, lighter
  - >100K diffs from OpenJDK

Illusions We Think We Have

- Thread priorities
  - Mostly none on Linux without *root* permission
  - But also relative to entire machine, not JVM
  - Means a low-priority JVM with high priority threads
    - e.g. Concurrent GC threads trying to keep up
  - ...can starve a medium-priority JVM
- Write-once-run-anywhere
  - Scale matters: programs for very small or very large machines are different

Illusions We Think We Have

- Finalizers are Useful
  - They suck for reclaiming OS resources
    - Because no timeliness guarantees
    - Code "eventually" runs, but might be never
    - e.g. Tomcat requires a out-of-file-handles situation trigger a FullGC to reclaim finalizers to recycle OS file handles
- What other out-of-OS resources situations need to trigger a GC?
- Do we really want to code our programs this way?

Illusions We Think We Have

- Soft, Phantom Refs are Useful
  - Again using GC to manage a user resource
  - e.g. Use GC to manage Caches
- Low memory causes
  rapid GC cycles causes
  soft refs to flush causes
  caches to empty causes
  more cache misses causes
  more application work causes
  more allocation causes
  rapid GC cycles

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Services Summary

- Services provided by JVM
  - GC, JIT'ing, JMM, thread management, fast time
  - Hiding CPU details & hardware memory model
- Services provided below the JVM (OS)
  - Threads, context switching, priorities, I/O, files, virtual memory protection,
- Services provided above the JVM (App)
  - Threadpools & worklists, transactions, cypto, caching, models of concurrent programming
  - Alt languages: new dispatch, big ints, alt conc

Move to OS: Fast Quality Time

- JVM provides *fast quality* time
  - Fast not quality from X86 'tsc'
  - Quality not fast from OS gettimeofday
- This should be an OS service
  - Tick memory word 1000/sec
    - Update with kernel thread or timer
  - Read-only process-shared page
  - This CTM is a coherent across CPUs on a clock-cycle basis

Move to OS: Thread Priorities

- OS provides thread priorities at the process level
  - Higher priority JVMs can/should starve lower ones
- JVM also needs thread priorities within-process
  - GC threads need cycles before mutator threads
    - Or else that concurrent GC will won't be concurrent
    - And the mutator will block for a GC cycle
  - JIT threads need cycles
    - Or else the 1000-runnable threads will starve the JIT
    - And the program will always run interpreted

Move to OS: Thread Priorities

- Right now Azul is faking thread priorities
  - With duty-cycle style locks & blocks
  - Required for a low-pause concurrent collector
- Per-process Thread Priorities belong in the OS
  - OS already does process priorities & context switches
  - Also, cannot raise thread priorities without 'root'
  - Lowering mutator priorities changes behavior wrt non-Java processes

Keep Above JVM: Alternative Concurrency

- JVM provides thread management, fast locks
- Many new langs have new concurrency ideas
  - Actors, Msg-passing, STM, Fork/Join are a few
  - JVM too big, too slow to move fast here
  - Should experiment 'above' the JVM
  - ...at least until we get some concensus on **The Right Way To Do Concurrency**
  - Then JVM maybe provides building blocks
    - e.g. park/unpark or a specific kind of STM

Move to JVM: Fixnums

- Fixnums belong in the JVM, not language impl
- JVM provides 'int' & 'long'
  - Many languages want 'ideal int'
  - Obvious java translation to infinite math is inefficient
    - Really want some kind of tagged integer
    - Requires JIT support to be really efficient
  - I think "64bits ought to be enough for anybody"
    - You (app-level programmer) know if you might need more
    - Don't make everybody else pay for it

Keep in JVM: GC, JIT'ing, JMM, Type Safety

- JIT'ing (by itself) belongs above the OS and below the App – so in the JVM
- GC requires deep hooks into the JIT'ing process
  - And also makes sense below the App
- The JMM requires deep hooks into the JIT also
  - And again (mostly) makes sense below the App
  - Some alternative concurrency models
    would expose weaker MMs to the App,
    would enable faster, cheaper hardware
    – but this is still going require close JIT cooperation

Move Above JVM: OS Resource Lifetime

- Move outside-the-JVM resource lifetime control out of Finalizers
  - Make the app do e.g. ref-counting or 'arenas' or other lifetime management
  - Do not burden GC with knowledge that more of resource 'X' can be had running finalizers
- Move weak/soft/phantom refs to the App
  - GC should not change application semantics

Summary

OS	JVM	Application
Virtual-Memory	Type-Safe Memory GC JIT'ing & Code Management	Alternative-Concurrency STM / FJ
Context-Switches	JMM Fast Locks Thread Management Thread Priorities Fast Time	Fixnums
Files, I/O	OS Resource Management	Tail Calls Closures

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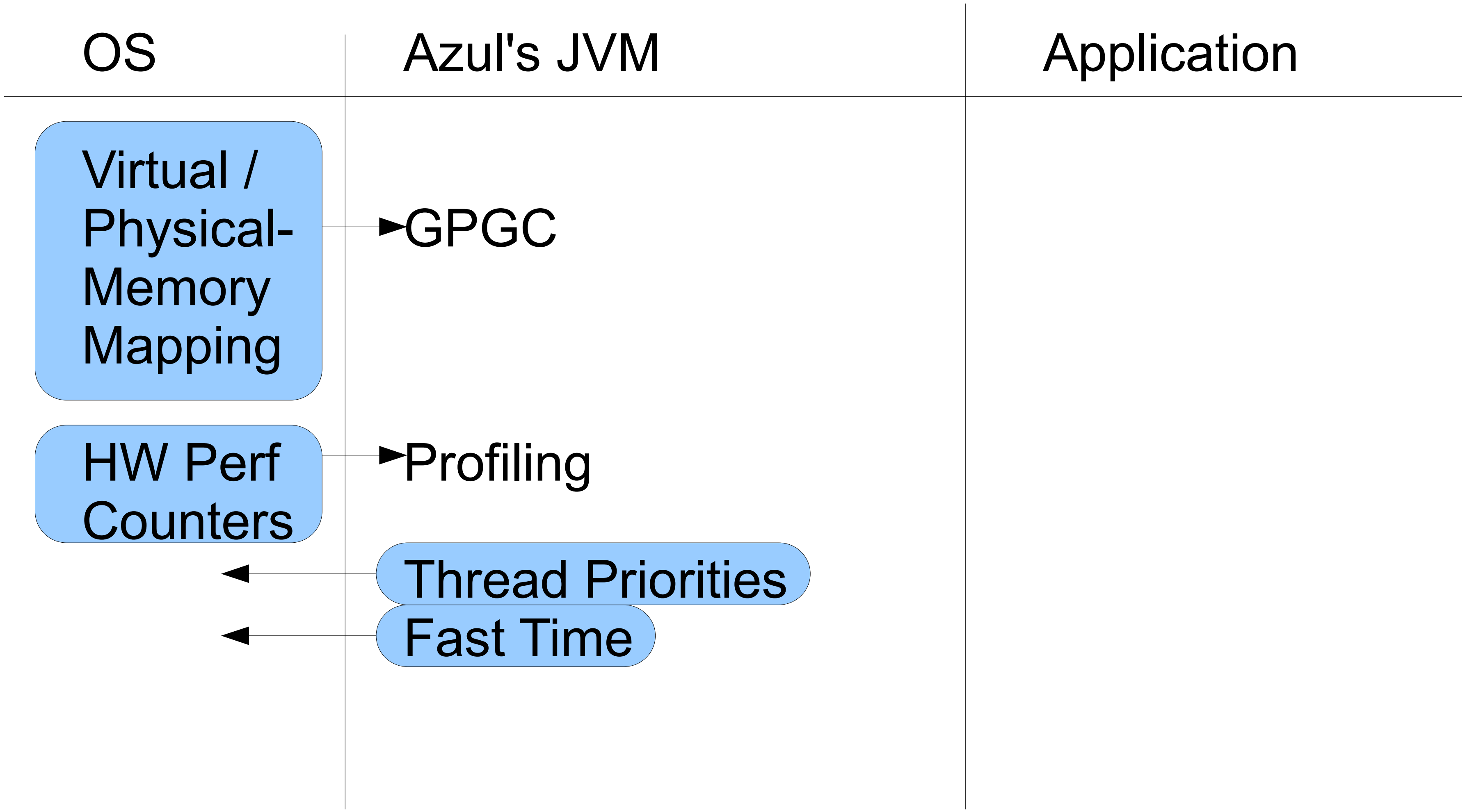
Move To JVM (Azul): Virtual / Physical Mappings

- Azul's GPGC does aggressive virtual-memory to physical-memory remappings
  - Tbytes/sec remapping rates
  - **`mmap()`** & friends too slow
- Need OS hacks to expose hardware TLB
  - Still safe across processes
  - But within process can totally screw self up

Move To JVM (Azul): Hardware Perf Counters

- JVM is already doing profile-directed compilation
  - Natural consumer of HW Perf Counters
- JVM can map perf counters to bytecodes
  - JIT's code, manages JIT'd code
  - "hotcode" mapped back to user's bytecodes
- Want quickest & thin-est way to expose HW perf counters to JVM

Summary (Azul)



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Summary

There's Work To Do

(full employment contract for JVM engineers)

PS: Azul is hiring compiler & runtime engineers

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