Arrays [ 2.0 \textsuperscript{64} ] – opportunities and challenges

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Why we can’t live without arrays

• Need at least one type with variable size!
  – Bucket for puddles of data. (Linked lists are only bandoliers.)

• Strongly typed (consonant with the rest of Java)
  – → must be generic

• Smallest memory footprint \((±\varepsilon)\)
  – → must have at least a few packed representations \((\text{byte}[])\)

• Efficiency: Minimum cache line accesses \((±\varepsilon)\)

• Notation (yes, notation counts when programming)
  – Definition: \(\text{int} \ a[] = \{1,2,3\}\);
  – Element access: \(a[1] += 5\);

• (Type safety and security are non-negotiable.)
Why arrays bother users

• Choose any flavor you want as long as it’s vanilla.
  – Length is never mutable. Body is always attached.
  – Elements are always homogeneous. (No C array+struct.)
  – Elements are always mutable (but never volatile).
  – Rank is always unity. Rows are always ragged.
  – Size is as big as you want, if you have modest expectations.

• T[] is covariant in T. (And there is no top Array type.)
  – Sometimes this seems to help. (Generic element types instead?)
  – Sometimes it’s just confusing.
  – Array store check is a hidden cost.

• Not a real object type. (Arrays.copyOf(a)!!)
  – Will the real toString method please expel the fake one?
Why arrays bother JVM implementors

• Lots of ad hoc special rules for arrays.
• Irregular appearance of fields and methods.
• Must provide generic instances Q[] on app. request.
• Suffer from megacephaly: Big headers.
  – Can you synch. on an array? Yes, but don’t.
• Big arrays provide bulky work units for GCs.
## My so-called Meme

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What Java coders say they want...

• Rank > 1 (Fortran matrices, etc.)
• Size $\geq 2^{31}$ (“long” indexes)
• operator overloading
  – $a[i], a[i]=x$ is really my method for my favorite array 1.01
  – maybe $a[i,j...]$; maybe $a[i]+=x$
  – *(hey, look at all those C++ and Scala folks having fun!)*
• layout control
  – array of structs; type with variable arrays
  – foreign (C) data access (w/ nio, JNI)
  – copy-free access to slices of data, scatter/gather
What Java coders say they want... (2)

• safe decomposition and sharing
  – final, volatile, etc.

• heterogeneous puddles of data
  – tagged data
  – buckets of less-structured data
  – serialization without tears (!?)
  – JSON/XML blobs (with pointers instead of bytes)

• flat-data performance
  – assume contiguous storage, close to the metal
  – dead-reckoned addresses → loop transforms in JIT
Speculative ravings follow!

- “View” of one Blind Man feeling the Elephant
- This is not a language design talk.
  - (Unless you believe invokedynamic is a language feature.)
- These thoughts are JVM-centric.
  - cowardly ducking away from controversy
  - most people care passionately about notation
  - JVM internals are mainly for us plumbers

- Let’s make progress...
What users "really" want (I think)

- Increase small scale collocation
  - Graceful use of cache lines
  - More dead reckoning of indexes; structs of arrays of structs
- Allow large-scale decomposition (tasks, etc.)
  - NOT large-scale contiguity (no terabyte memory blocks)
- Memory fencing/protection for safe sharing
- Compose complex sharing patterns
  - from a few independent and powerful primitives
rank: what the JVM should provide

• Which square matrix? Row-major? Col-major?
• About a dozen important sparse representations too.
• This is about cache-grace, not $A[i][j]$ vs. $A[i,j]$.
• Key operation: index computation
  – Must be a library-defined method, not a new part of the JVM.
• **Requirement:** Library definition of many array types.
• Key operation: loop decomposition
  – Today, this is a job for off-the-shelf BLAS/LAPACK type code.
  – Need to serialize chunk access between GC and BLAS
  – **Requirement:** pinning
bigness: what the JVM should provide

• Size $\geq 2^{31}$ $A[(\text{long})x] = 5$
  – Hard requirement? More like a “red face test”.

• **Warning**: Big (contiguous) Data $\rightarrow$ Big Copies

• **Requirement**: Library definition of array types.
  – Hello, Scala & Fortress!

• Anti-pattern: planet-sized contiguous memory chunks
  – Modern GCs are regionalized.
  – Regions are continents, not galaxies.
resize: what the JVM should provide

- Supply a safe resize operation for arrays.
  - But only to *decrease* size.
- `Arrays.chop(T[] a, int newlength)`
- Needed to reduce copying in `StringBuilder`, etc.
notation: what the JVM should provide

- **operator overloading?**
  - The JVM’s ops are `arraylength`, `aaload`, `iastore`, etc.
  - Also `System.arrayCopy`, `Arrays.copyOf`, etc.

- **Requirement: Re-interpret existing bytecodes**
  - as shorthand for patterns like `x.length()`
  - verifier & JVM still hardwires privileged legacy types
  - verifier treats `arraylength` as `invokevirtual`
  - descriptor is `A.getArrayLength()int` (with A from verifier)
layout: what the JVM should provide

• Need a little more from the GC / heap manager
  – GC owns low-level memory layouts
  – That’s where the cache help has to be.

• **Requirement:** hybrid arrays
  – GC sees object with length (like legacy arrays)

• “Envelope + body” are fused into “head + tail”.
  – Dead-reckoned addressing: sizeof(hdr) + sizeof(elm) * N
  – GC knows how to find references in head and tail.
  – **Requirement:** Tail can be periodic repetition of small struct.

• Java sees a plain instance
  – Head is a first-class Java object with methods and *everything*.
  – Tail is accessed by new intrinsics. Private to enclosing class.
layout: what the JVM should provide

- Foreign data can be accessed via Unsafe.
- This should be encapsulated via header file import.
- Cf. CLR “delegate marshalling”, etc.
- LAPACK/BLAS needs to dictate layout details.
  - Copy-on-involve is a lose.
  - ...Although the memory fabric is surely doing copies.
  - ...But we don’t want the JVM to interpose on memory ops!
hybrid arrays in the VM

• From our SCCS history, for Klass::layout_helper
  – src/share/vm/oops/SCCS/s.klass.hpp
  – D 1.136 07/01/29 21:20:30 jrose 281 280
  – c 6516018 Replace size_helper and is_objArray by more capable layout_helper.

• The layout-helper allows arbitrary (small) header size
  – lh_header_size_mask = 0xFF    // :-)  
  – This is where the instance variables will go!
sharing: what the JVM should provide

• How to share?
• Java arrays are an uneasy fit in the JMM
• Key idea: JMM assumes *serialized access*
  – Also multiple-readers of final values.
• **Requirement:** memory fences for arrays.
  – Explicit release and acquire for array slices.
  – (JMM experts, please correct this!)
• Key use case: Partition a work set w/o copying.
  – Fork, join, steal, repeat.
tags: what the JVM should provide

- heterogeneous containment?
- standard boxing is not cache-graceful
- fixnums? tagged unions? (working on this...)
- periodic-array-of-struct will reduce pressure for this
- but may still need *non-periodic sequences*
flatness: what the JVM should provide

• flat data, *but please don't look behind the curtain*
  – assume flat storage, but there can be no proof
• trust JVM to provide as-if-flat performance (or better)
• low-pause technologies can help (“arraylets”)
• **Claim:** There is a *natural largest scale* for flat data.
More about library types

• in one step remove size & rank limits
• encapsulate complex layout algorithms
• **Requirement:** Value types for small structs / tuples
  – [https://blogs.oracle.com/jrose/entry/value_types_in_the_vm](https://blogs.oracle.com/jrose/entry/value_types_in_the_vm)
• We still need to build on nio, unsafe, etc.
• Hybrid arrays can be built from Java + MHs + unsafe
  – Existing `newInvokeSpecial` direct MH does this now.
  – Can build new ones that incorporate the hybrid “tail”.
• Non-periodic access can be done cheaply
  – Assuming encapsulated cursor values, with scalarization.
• Possible to build many patterns from few primitives.
What library types can define...

- Index width, number of indexes
- *Type* of indexes (associative arrays)
- Resize capability (how many indirections?)
- Periodicity (random vs. streaming access)
- Storage classes (final, volatile)
- Fencing / sharing / serialized access
- Compound or BLAS operations
- Super types
- Convenience methods
- Contiguity
More about operator overloading

• No, we won’t go and be C++!
• Java has to be “close to the metal”. No surprises.
• Even library-defined arrays have to avoid surprises
  – No excessive layers of indirection or cache accesses.
  – This is why we need hybrids.
• Probably just `getArrayElement`, `setArrayElement`
• slicing? (lvalues, index ranges): can do with libraries
  – work as much as possible within the existing language
  – (syntax, op spellings)
• for complex, application-specific notations: DSLs!
• residual language extension: allow multi-arg `a[i,j,k]`
Hard problem: Type templating

• Array appear to require a templating mechanism.
  – Type erasure won’t cut it, if you want primitives & structs.

• General-case reification not needed
  – Library classes can record “type dope” in ad hoc manner.
  – Cf. checked versions of list, set, etc.
Hard problem: Type templating (2)

• Need something like this:
  
```java
template class BigSparseArray<template E>
   extends template ? super BigSparseArray<E>
{
   public E getArrayElement(long x) { ... } 
}
```

• Type parameter(s) matches a “hole” in the body.
  – Holes are filled in by copying and pasting, in class loader.
  – Requires explicit value (struct) types to maintain sanity.
    
```java
value E getArrayElement(long x) { ... } 
ref    E getArrayElement(long x) { ... } 
```
Power tools: JSR 292

- invokedynamic for truly new instructions (needed?)
- method handles for composing hybrid objects
  - `new_hybrid_object` + `invokespecial` (of regular constructor)
- maybe, method handles for privileged intrinsics
- New JVM pattern: Bootstrap method
  - Statically defined, lazily called method with static arguments.
- Possible BSM use cases
  - On-the-fly template instantiation (class loader calls BSM)
  - Use (with indy?) for defining the “holes” in a template.
  - Use for native method definition.
  - Useful for “intercessory” metaobject queries.
Killer Use Cases for Arrays 2.0

• fused (1-node) implementation of `java.lang.String`
  – | header | length | hash | body | → | header2 | char[] |

• cache-graceful impl. of `HashMap<Integer,String>`
  – Should be an array of struct `{ int, ref }`.
  – 2-node representation. Envelope needed for resizing.

• cache-graceful B... trees (finally!)

• views on foreign data ( `N^2IO Direct{Data}Buffer` )

• (your contribution here...)

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Questions?

(where’s the outrage?)