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Data parallel programming and Java

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What is “data parallel” computing?

- Divide and conquer
  - Data is broken up into chunks (inputs, outputs, temps)
  - Each chunk is processed independently from the others
- Homogeneous computation
  - All the freedom is in the data, not the code
  - Operations are about the same everywhere
- Hardware requirements are modest
  - Easy to compile to vectorized loops (Haswell, etc.)
  - Easy to avoid branches; accepts deeply pipelined CPUs
  - Synergizes with array-wise prefetch through memory fabric
  - Also works fine on “Single Instruction Multiple Data” hardware

Running example: sum of C ← A + B

- In classic Java:

```
for (int i = 0; i < A.length; i++)
  C[i] = A[i] + B[i];
```

- Fortran 95 explicit loop:

```
FORALL (I = 1:N) C(I) = A(I) + B(I)
```

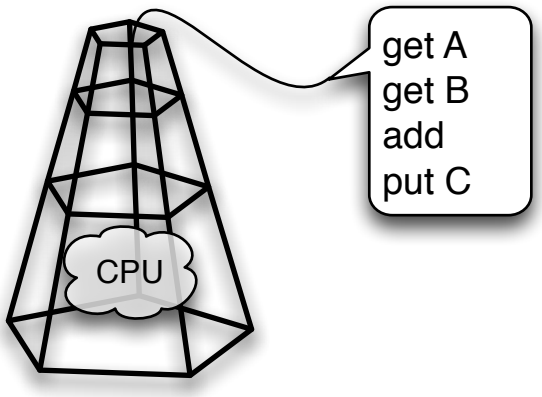
- Array languages (Fortran, R, Matlab, APL):

```
C "gets" A + B
```

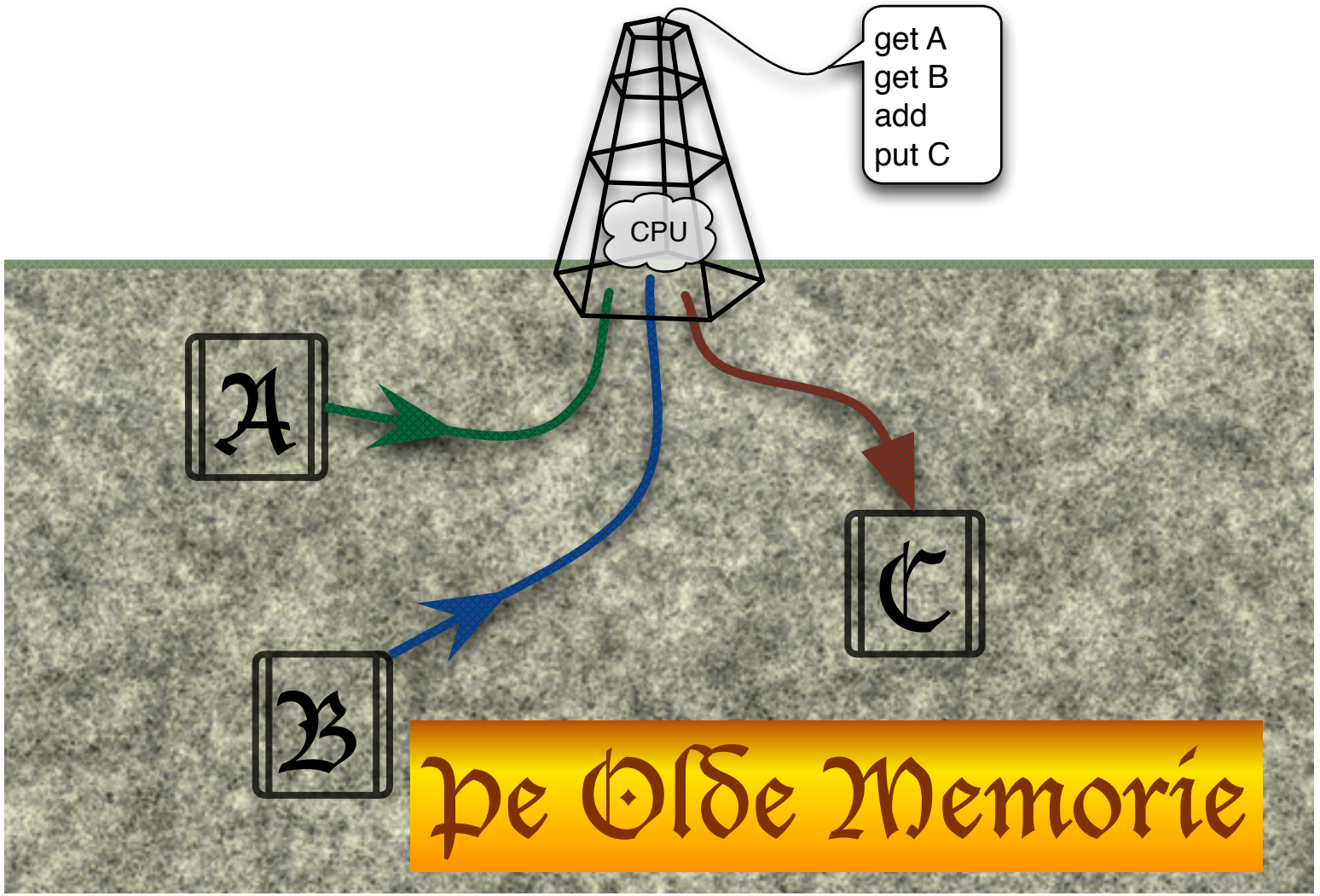
- In JDK 8 streams:

```
IntStream.range(0, A.length).parallel()
  .mapToDouble(i->A[i]+B[i])
    .toArray()
```

Can a coder dream of electric chips?



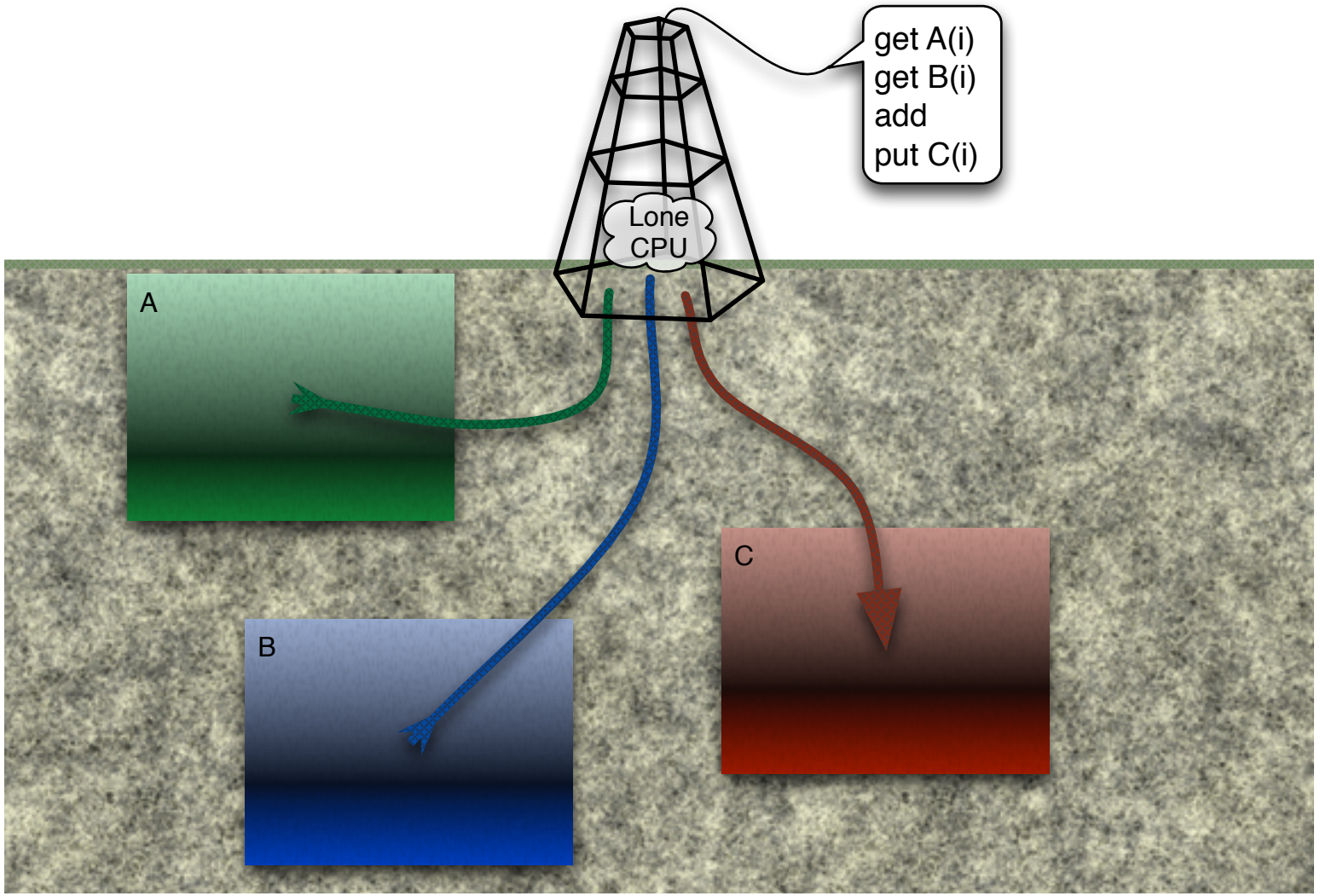
An ordinary load-store machine



working assumption: data = arrays

- little loss of generality to assume array-like data
  - linked lists or iterators are not sub-dividable
  - ArrayList is OK, of course, and so are buffers (NIO, etc.)
  - JDK 8 “spliterators” can be buffered in medium-sized arrays
- key properties of arrays and array-likes
  - subdivision is cheap (log or constant time)
  - streaming over subdivisions is cheap (linear with prefetch)
  - concurrent access to disjoint subdivisions is non-interfering
- classic Java arrays are OK but not exactly right
  - #include <arrays 2.0 talk>

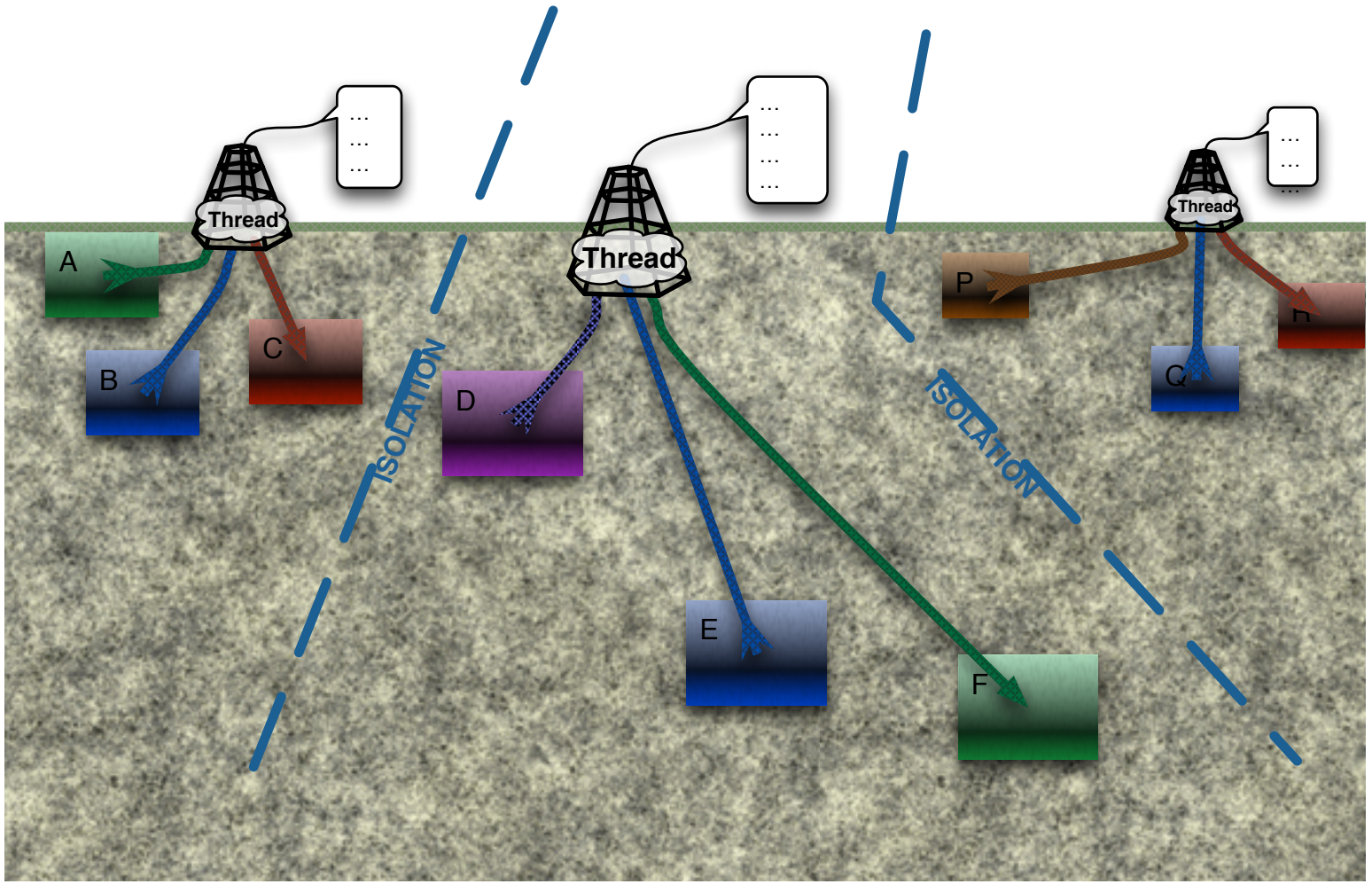
Load-store machine, with arrays



How the Java VM virtualizes a CPU

- a thread (usually more than one) containing:
  - a bytecode instruction stream
  - stack frames containing variables and other goodies
  - enough raw stack to make SOE rare in practice
- a big shared memory containing:
  - contains simple structs and arrays
  - self-identifying (reflectable) data and managed pointers
  - enough raw heap to make OOME rare in practice
- concurrency rules which:
  - reconcile local thread R/W actions with global state
  - provide ways to coordinate via synchronization events
  - give just enough *happens-before* relations to avoid bad races

So let's go multi-threaded!



Old school multi-threading

- "MIMD" = Multiple Instruction Multiple Data
  - very general
  - works fine if thread effects are disjoint
  - mix in with mutable data everywhere for extra "generality"
- code must synchronize carefully
  - any other thread might be executing any other code
  - it is difficult to reason about all possible interleavings
- footprint from a big, rich `java.lang.Thread` object
  - requires a large pre-allocated control stack
  - comes with extra amenities like `java.lang.ThreadLocal`

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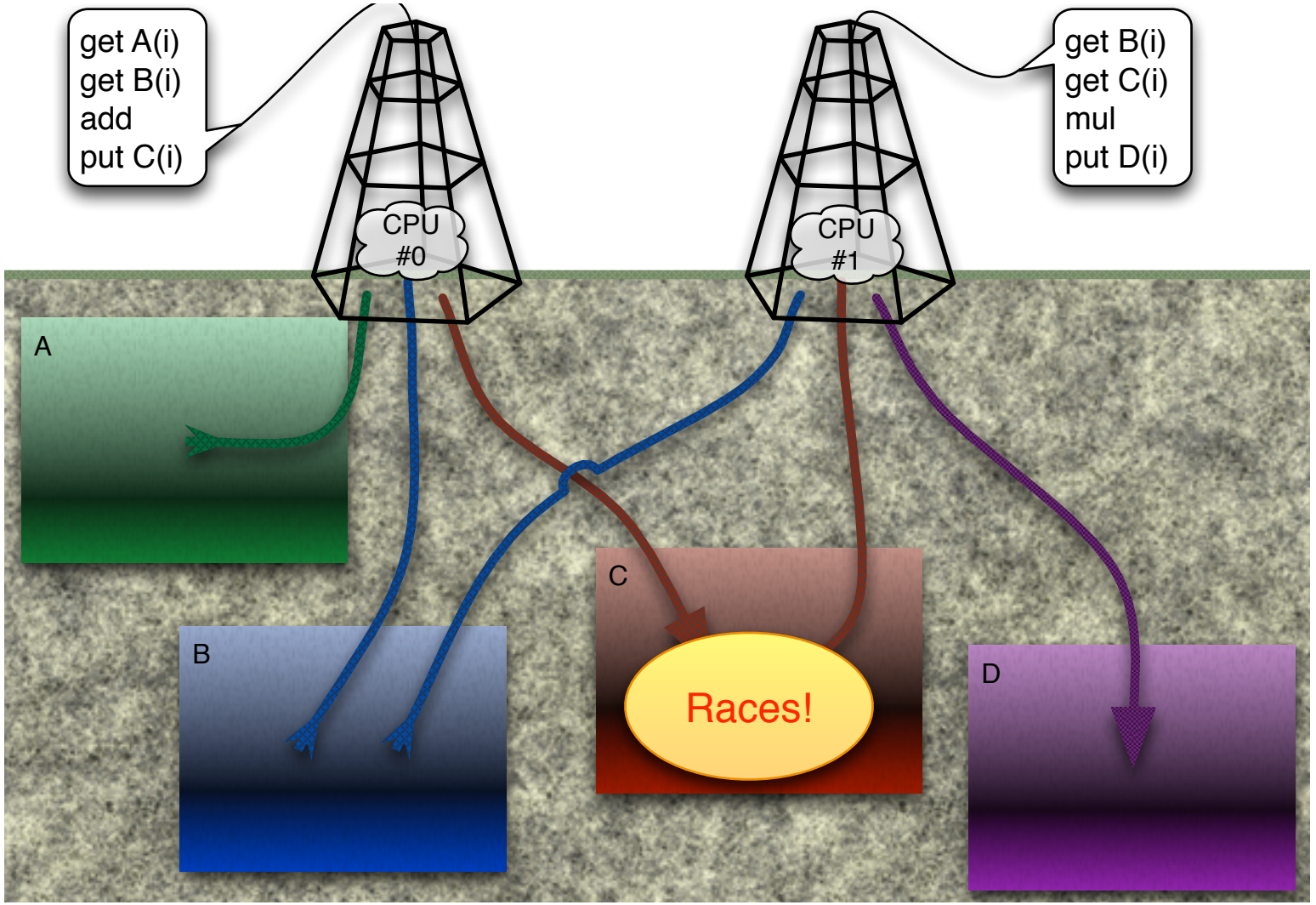
Threads can step on each others' toes



What went wrong?

- The “Central” aspect of “CPU” causes bugs
  - the memory is central (if anything is); processing is not
- An output of CPU#0 was a racy input of CPU#1
  - Best practice: “Settle” and freeze input arrays before use.
  - Value Objects JEP includes a “freeze array” operator.
- Problems also arise if two CPUs use the same output
  - Best practice: Write each output variable exactly once.
  - Create outputs late and fully formed – `Stream.toArray`

BTW, what is right, despite?

- Bytecode semantics
  - valuable medium-level notation, workable in SIMD & MIMD
- Managed heap, concurrency model, safety/security
- Supported: objects, methods, lambdas, streams, etc.
- Both high-level APIs and low-level utilities

- Let's keep all that...

In search of the right notation

- MIMD is overly general for simple things like C=A+B
  - loops promise too much sequencing; also verbose
- For many end-users, streams give simple power
  - “just add dot-parallel” – reasonable recipe, JVM must honor
- Bulk array-oriented operations are friendly too
  - note deep popularity of R language
  - looping is implicitly supplied from array shape rules
  - room here, maybe, for a DSL in Java some day
  - for a quick win, consider injecting Arrays into T[] via defaults
- Low-level big array of small pre-placed structs
  - (a la *Lisp, C*; more later)

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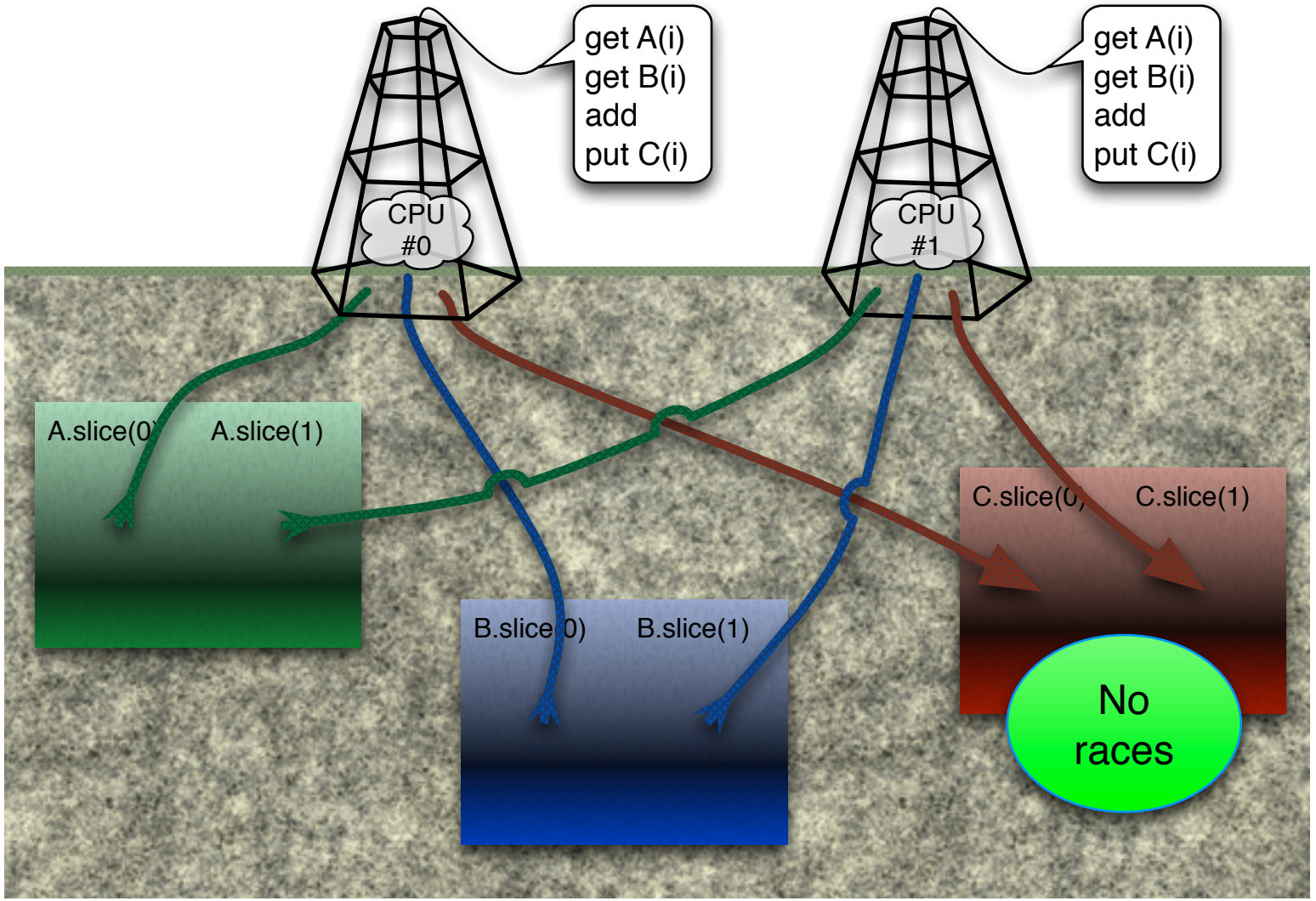
Timing can be everything

- User model and notation must explain sequencing
  - (at least to the extent that there are side effects underfoot)
- Can set concurrency rules various ways:
  - global clock (lockstep per bytecode, or hidden loops)
  - local clocks with explicit synch. handshakes
  - queues, dataflow? (at which scale?) – streams feel better
  - warps (thread swarms) – divergence can be a problem here
  - library framework schedules callbacks (GCD, FJ, streams)
- To avoid stepping on your partner's foot, try lockstep
  - (If you still stomp the foot, it will be much more predictable.)

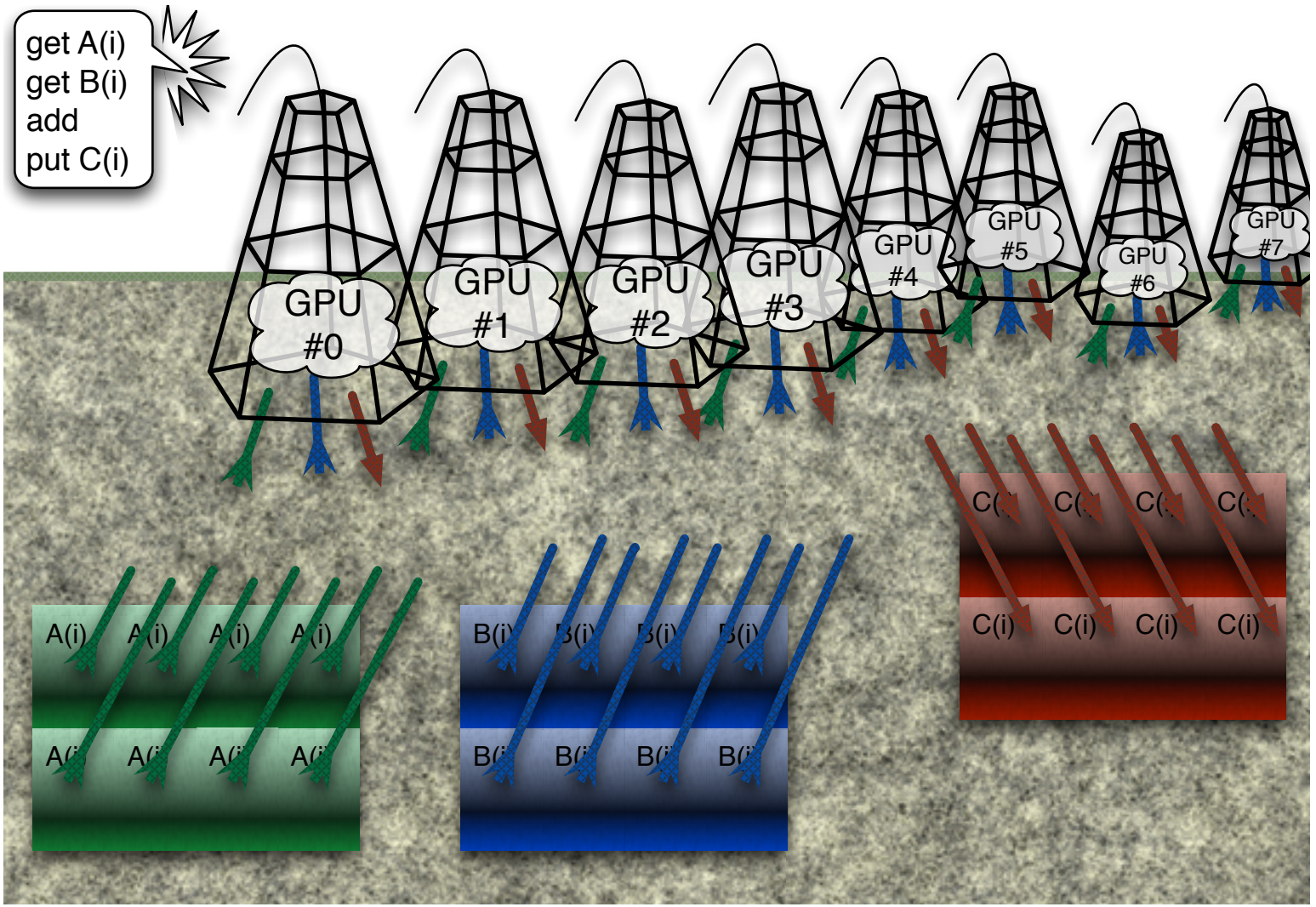
Partition the data, not the code



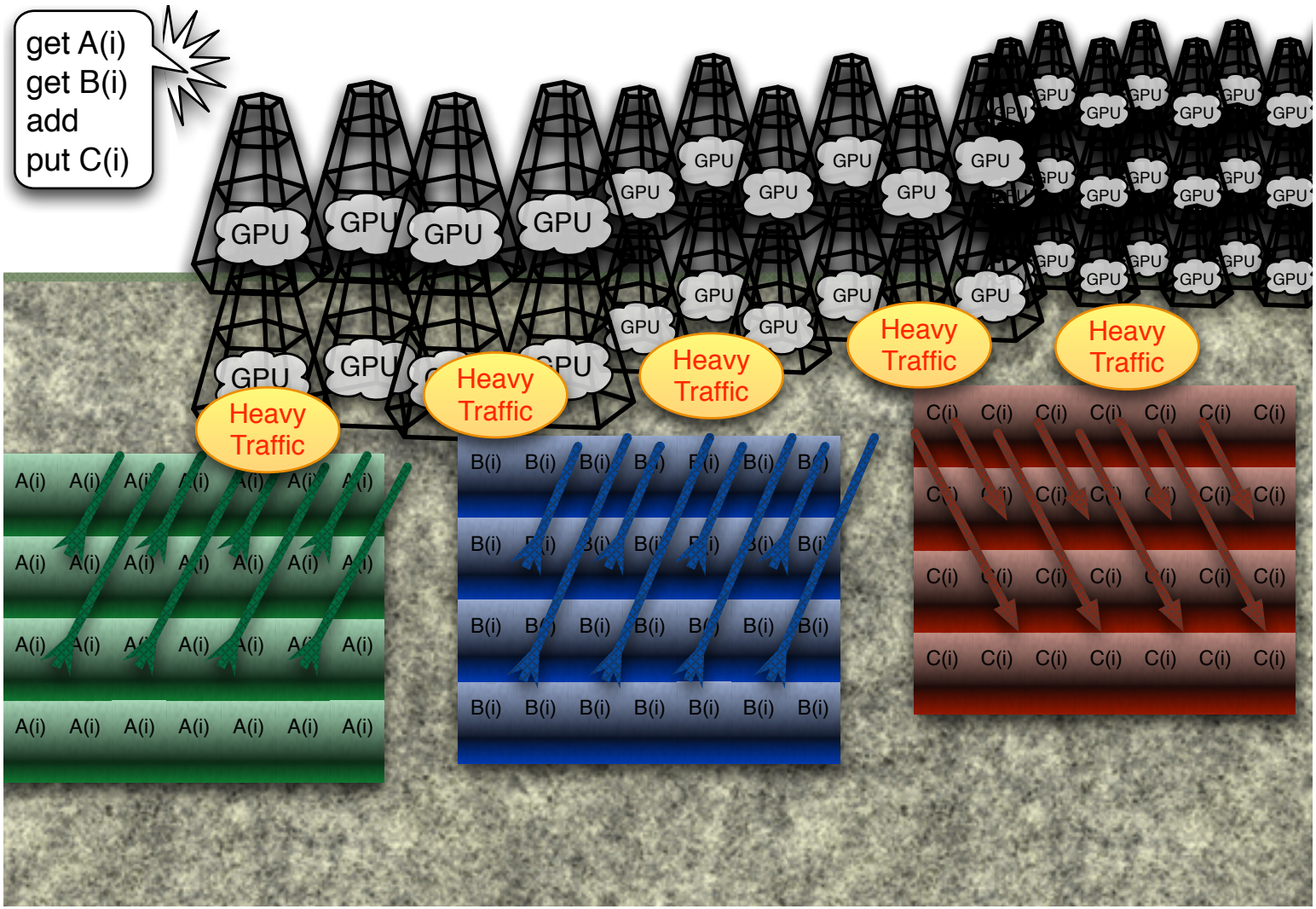
Partitioned data is naturally simple

- "SIMD" = Single Instruction Multiple Data
  - I.e., you want to do the same thing in each part of the data
- The "loop body" may have effects
- The effects will run in an arbitrary order
  - and this must not effect the outcome of the computation
- A full range of loop transforms can be applied
  - unroll/vectorize, buffer/prefetch, fork/join
- There may also be hardware efficiencies
  - One instruction unit broadcasting to several data pipes
  - (Not clear this is a big win, but I'm just a software guy.)

Split the data, keep one code stream



What could go wrong?



Communication dominates eventually

- Could express communication directly (pipes, MPI)
  - Does not leverage nice big shared memory – not JVM-ish
- Could add “placement” to types
  - Java “typefulness” is limited – `cpu2.new PlacedArray` ??
- Could add “placement” to objects
  - Would include explicit move (= “marshal”) operators
  - Feels like manual storage management; want to do better
- Contention: The JVM should control copying
  - GC “marshals” objects from newspace to oldspace
  - Moving data “near” to processing elements is JVM-ish job
  - JVM can use profiling, optimistic techniques, etc.

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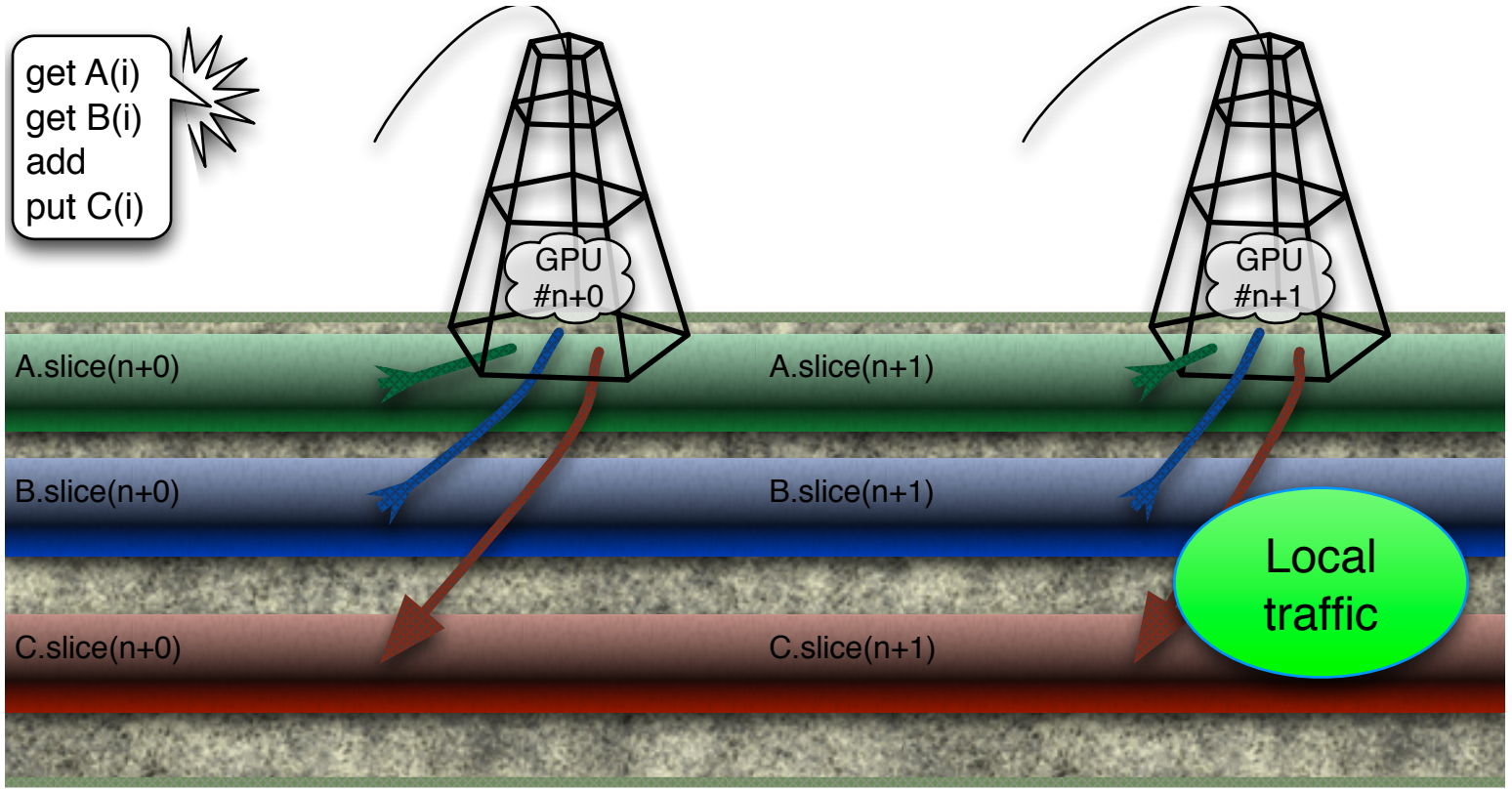
Let's stripe the data across the CPUs



Options for localizing data

- Manual (malloc/free): error prone
  - Also non-concurrent, which means chunk-sized latencies
  - Latencies make it hard to win compared with “JIT” fabrics
- Software caching/paging
  - JVM or some JDK framework manages local memories
- Hardware caching/paging
  - Yes, please. (Said the software guy.)
  - The option with the most low-level concurrency (prefetching)
  - This is a promising aspect of the HSA.

Options for localizing data (2)

- What if we don't have hardware caching?
  - Then we need rough equivalents
  - Need array-like objects which can be marshalled in chunks
  - Each chunk must be be separately bindable to a processor
  - Must also have a broadcast option (RTS instead of RTO)
- These features don't work with classic Java arrays!
- New arrays could have owner-thread safety rules
  - with runtime checking, same as for array bounds and null
  - would have to allow partitioning across multiple owners

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What is a Java “GPU thread”?

- Must *not* be a subclass of `java.lang.Thread`!
  - Too much overhead from stack, etc.
- Minimally, it is a single iteration of the FORALL loop
  - Compare with other notions of “strand” or coroutine
  - Executes a (mainly linear) series of Java instructions
  - “Knows” which iteration it is doing (cf. GPU work item ID)
- Maximally, the whole loop, but cleverly decomposed
  - We don’t want to decompose Java “for” loops.
  - But Java (8) streams are designed to decompose!
- Somewhere in the middle, it is a “chunk” of iterations
  - Length is of the order |total size|/(#processors)
  - Library writers work with such loop chunks

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What is a Java “GPU thread”? (2)

- Virtual “GPU thread” should be as light as possible.
  - But, no user-visible semantic differences for bytecodes
- Suggestion: Do not reify, except as an index value
  - ...such as the result of `IntStream.range(0, N)`.
  - “Thread” execution consists of a lambda with parameter(s)
  - For 2D or 3D, could be a tuple of index values
- Moreover, `Thread.current` should return a dummy
  - Look to coroutine experiments for insight
- More detailed comparison with classic threads here:
  - http://wiki.openjdk.java.net/display/Sumatra/Thread+Swarms
- Perhaps this is a “thread swarm” or “warp”:
  - `s.parallel().forEach(x -> (#))`

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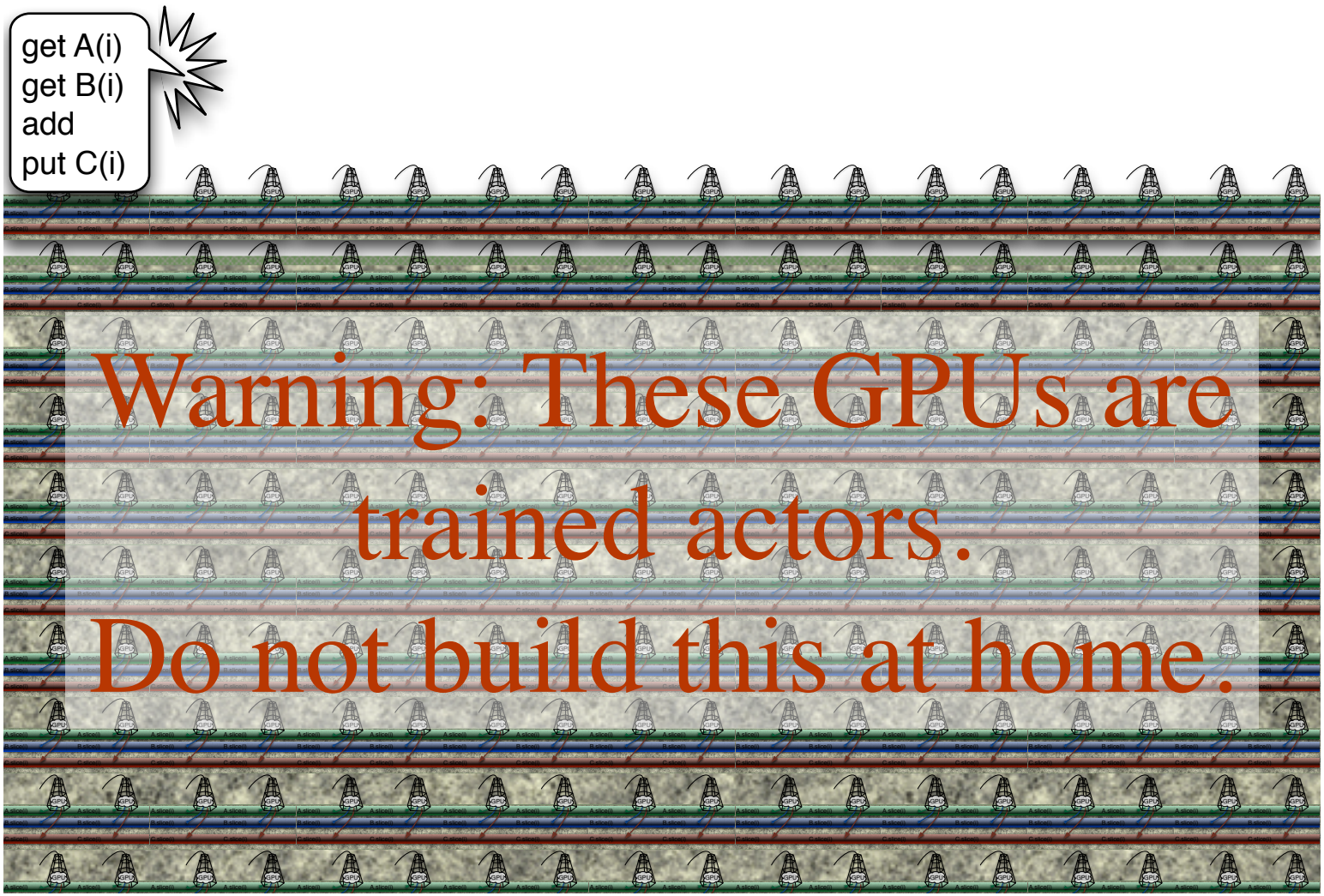
This works — virtually



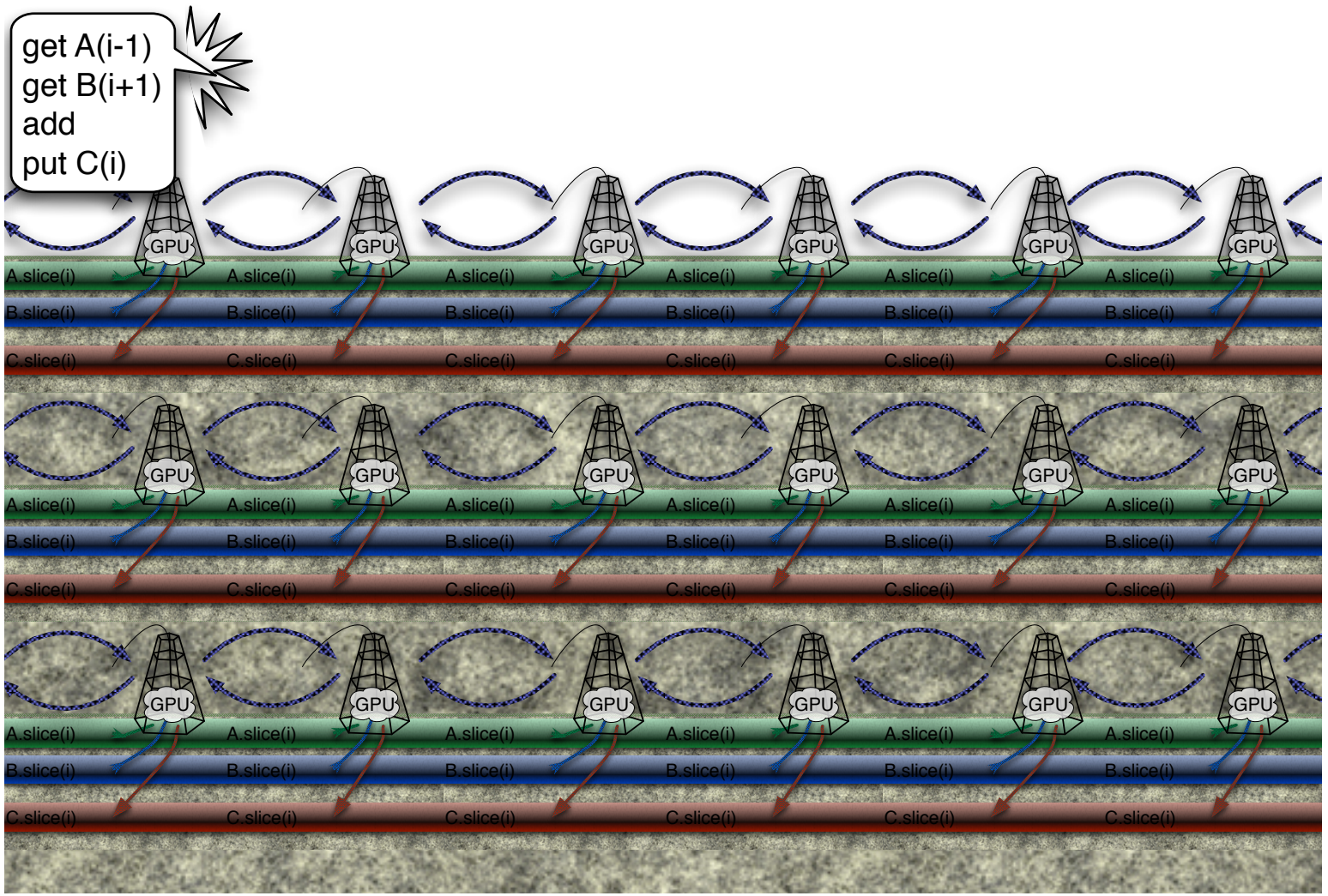
Issue: Placed data needs to be aligned

- In the running example, A, B, and C are aligned
  - If some chunk of A is partitioned onto some local memory...
  - ...then the corresponding chunk of B must follow
- Relates to the APL-ish idea of “shape conformance”
  - Also found in highly explicit languages like *Lisp and C*
  - Abstracted under the term “paralation” (Sabot)
- JDK 8 stream code generates a stream of indexes
  - The lambda (`i->A[i]+B[i]`) expresses A/B alignment
  - This is opaque to everybody but the JVM.
- Tentative corollary:
  Whatever “`Q[i]`” is, must be prefetchable/moveable

Regarding *local* communication

- The foregoing assumes completely “elemental” ops
  - C(i) depends only on A(i) and B(i)
- But the points apply just as well if neighbors can talk
  - A “stencil”: C(i) might depend on A(i-1), A(i+1), B(i-1), etc.
  - Loop transforms can deal with such mesh-like effects.
  - And many computational algorithms depend on meshes.

Mesh computing, with private memory



Slightly less local communication

- Non-neighbors can play too, if there are not too many
- Each iteration could do a heap access or table lookup
  - This works best if the looked-up data is sharable (RTS)
  - Sharability is one reason value objects are important
- Real GPUs need to simulate Java safety checks
  - NPE/RCE, div-by-zero or other errors will cause divergence
  - Rule of thumb? The less local the information, the more noisy

Global but log-scale communication

- The foregoing points also apply for reductions
  - Parallel reduction requires a O(log N) spanning tree.
  - Same for scans — JDK 8 `Arrays.parallelPrefix`
- JDK 8 reduction & scan works this way out of the box
  - including user-defined reduction ops!
- *Segmented* parallel prefix is a powerful building block
  - Can represented “nested” parallelism by flattening with keys
  - Might support the JDK 8 `groupingBy` collection operator

Regarding vectorization

- Modern hardware supplies efficient small vectors
  - small = cache-line granularity
  - efficient = SIMD across vector elements in a cycle or so
- These vectors operate independently of big arrays
  - but are a useful building block for all kinds of loops
  - some libraries build up mega-vectors from small ones
    - example: CVL (Blelloch)
- Open question: Does Java need a vector type?
  - Likely answer: Library writers may need them.
  - Likely answer: Compilers will want to emit them.
  - This is a use case for “value objects”.

Summary: Java liabilities / challenges

- Heavy threads
- Object state even when you don’t want it
  - Ditto for object locks and object reference identity
- Classic arrays (more wide-open state than Alaska)

Summary: Java assets

- Clean memory model
  - including final variables and eventually value types
  - model deeply supports concurrency
- O-O and/or ADT encapsulation
  - when we can wrap arrays we can tame them
- JDK 8 lambda-based streams
  - much good stuff right out of the box

Yes, but the question is...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