Supporting the many flavors of parallel programming

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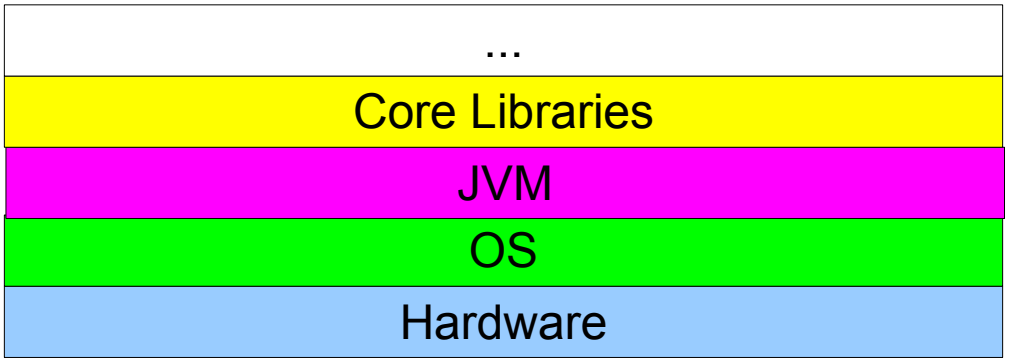
Outline

- **Parallelism**
  - **Transition from hidden implementation techniques to supporting explicit parallel/concurrent programming**
    - **Most techniques that make systems faster involve parallelism**
    - **Within and across layers**



- **Diversity**
  - **Ideas behind support for some parallel FP, OO, and ADT based styles, patterns, and idioms**

Parallelism in Implementations

- Over forty years of parallelism and asynchrony in implementations for commodity platforms
  - Overlapped IO and device control
  - OS Processes and scheduling
  - Networked/distributed system handlers/modules
  - Event/GUI handlers; interrupts
  - Superscalar, out-of-order ALUs
  - Custom co-processors, ASICs, GPUs etc
  - Concurrent garbage collection and VM services
- Result in better throughput and/or latency
  - But point-wise, quirky; no grand plan
  - Complex performance models

Exposing Parallelism

Old Elitism: Hide from most programmers

- "Programmers think sequentially"
- "Only an expert should try to write a <X>"
- "<Y> is a kewl hack but too weird to export"

End of an Era

- Few remaining hide-able speedups (Amdahls law)
- Hiding is impossible with multicores, GPUs, FPGAs

New Populism: Embrace and rationalize

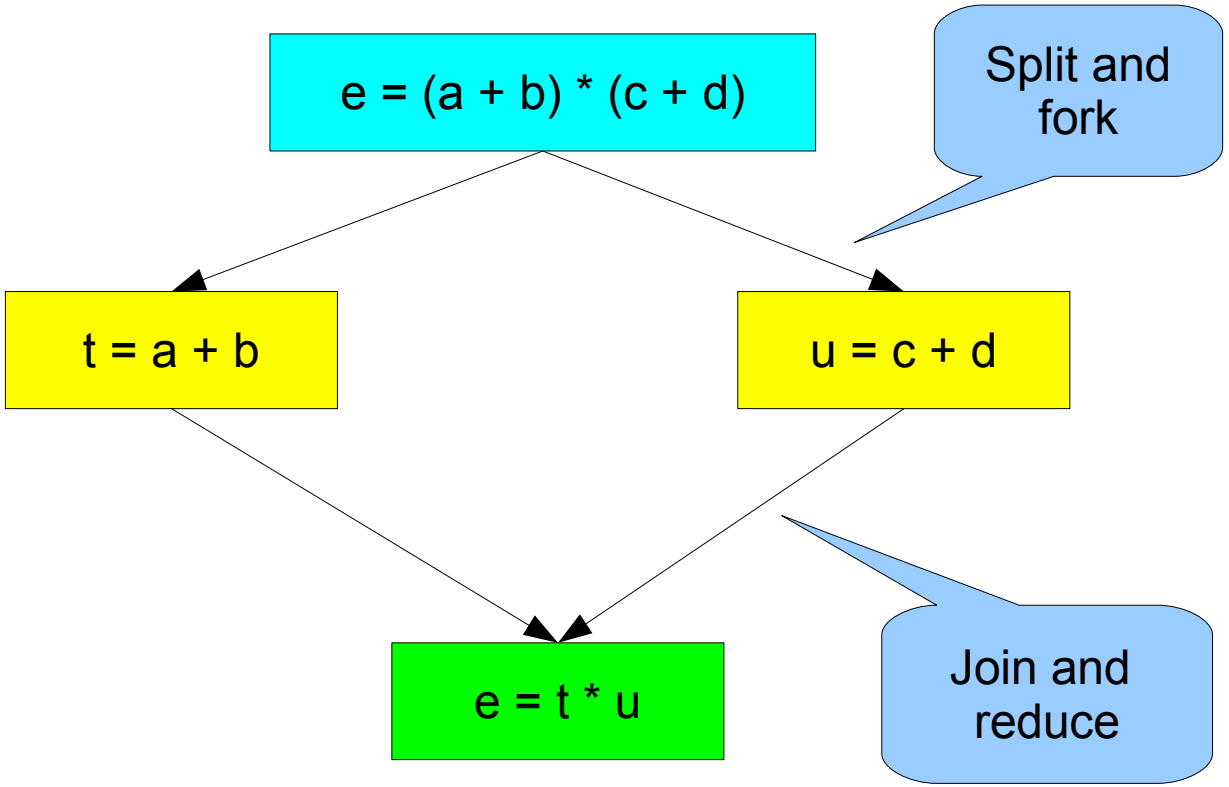
- Must integrate with defensible programming models, language support, and APIs
- Some residual quirkiness is inevitable

Diversity

Parallel and concurrent programming have many roots

- **Functional, Object-oriented, and ADT-based procedural patterns are all well-represented; including:**
  - **Parallel (function) evaluation**
  - **Bulk operations on aggregates (map, reduce etc)**
  - **Shared resources (shared registries, transactions)**
  - **Sending messages and events among objects**
- **But none map uniformly to platforms**
  - **Beliefs that any are most fundamental are delusional**
  - **Arguments that any are “best” are silly**

Parallel Evaluation

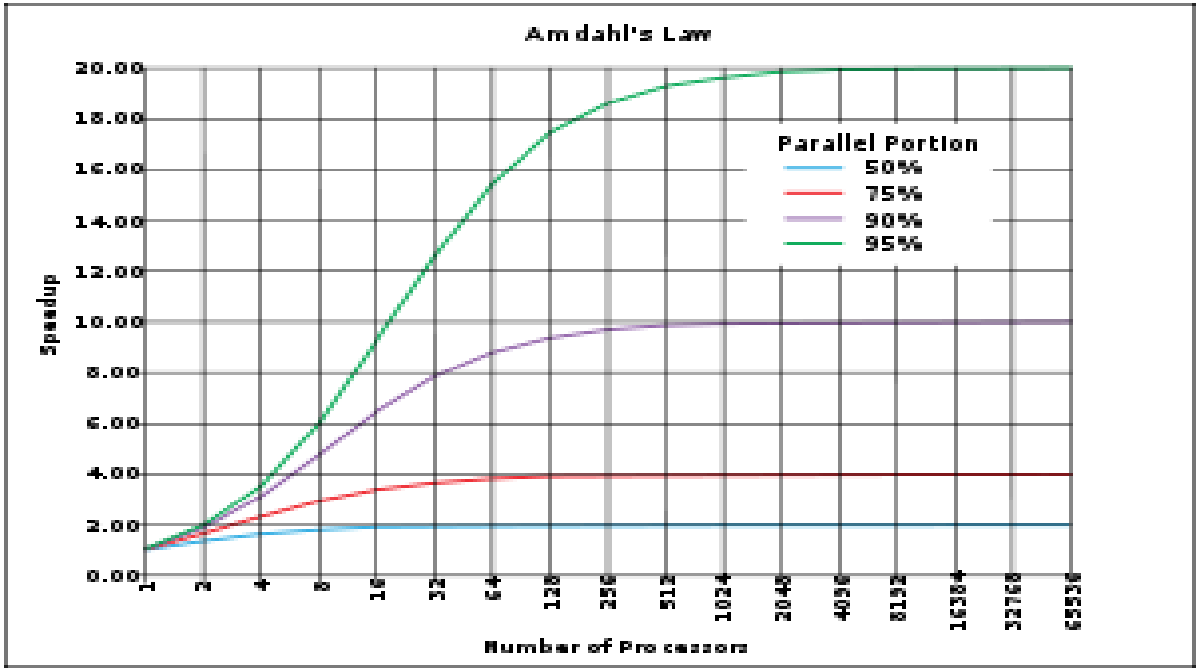


Parallel divide and conquer

Limits of Parallel Evaluation

- Why can't we always parallelize to turn any O(N) problem into O(N / #processors)?
  - Sequential dependencies and resource bottlenecks
- For program with serial time S, and parallelizable fraction f, max speedup regardless of #proc is 1 / ((1 – f) + f / S)
- Can also express in terms of critical paths or tree depths

Wikipedia



Parallel Evaluation inside CPUs

Goal: Parallelize basic expressions

- Problem: Instructions are in sequential stream

Idea: Dependency-based execution

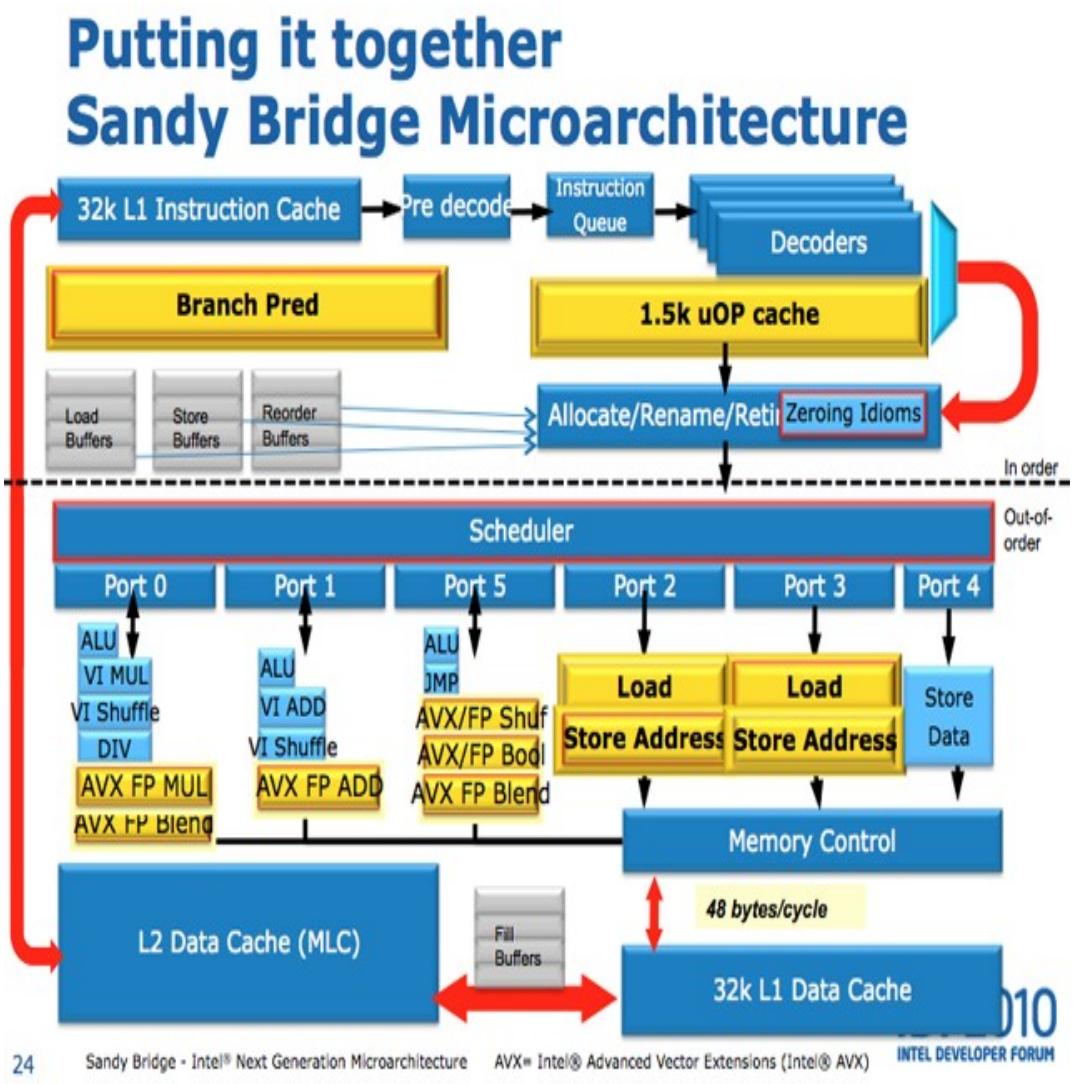
- Complete instructions when inputs are ready (from memory reads or ops) and outputs are available
  - Uses a hardware-based variant of dataflow analysis
- Pipelines, buffered in-flight instructions, out-of-order processing, multiple ALUs, store buffers, etc

Problem: It is always on!

- Dependency analysis is shallow, local, and may not match (concurrent) program semantics
- Undefined in presence of races: what if another processor modifies a variable accessed in an instruction?

Shallow Dependencies

- Assumes current core *owns* inputs & outputs
  - Not always so in explicitly concurrent programs
    - (Examples later)
  - Special instructions (fences etc) to enforce ordering
  - One reason languages need Memory Models



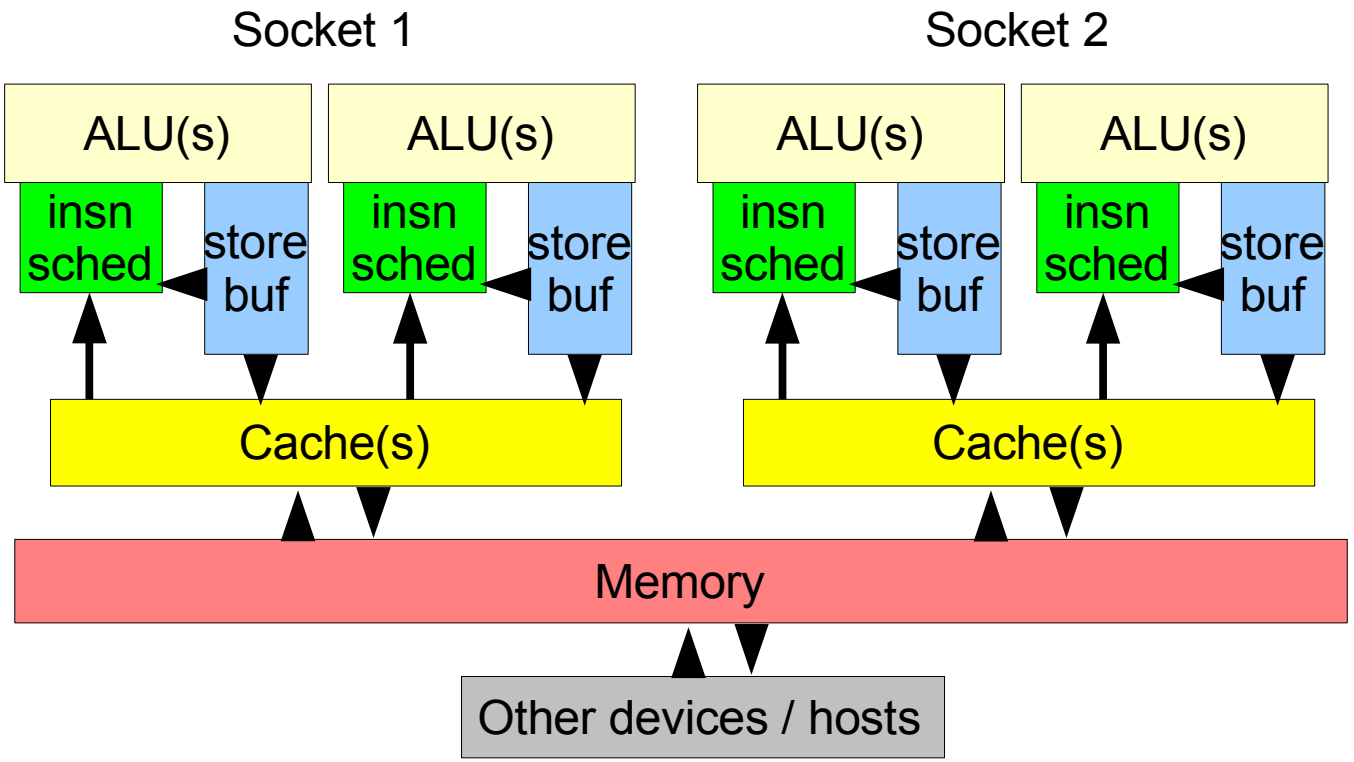
Ars Technica

Parallelizing Arbitrary Expressions

- Instruction-level parallelism doesn't scale well
  - But can use similar ideas on multicores
  - With similar benefits and issues
- Example: val e = f(a, b) op g(c, d)
- Easiest if rely on shallow dependency analysis
  - Methods f and g are pure, independent functions
  - Can exploit commutativity and/or associativity
- Other cases require harder work
  - To find smaller-granularity independence properties
    - For example, parallel sorting, graph algorithms
  - Harder work → more bugs; sometimes more payoff

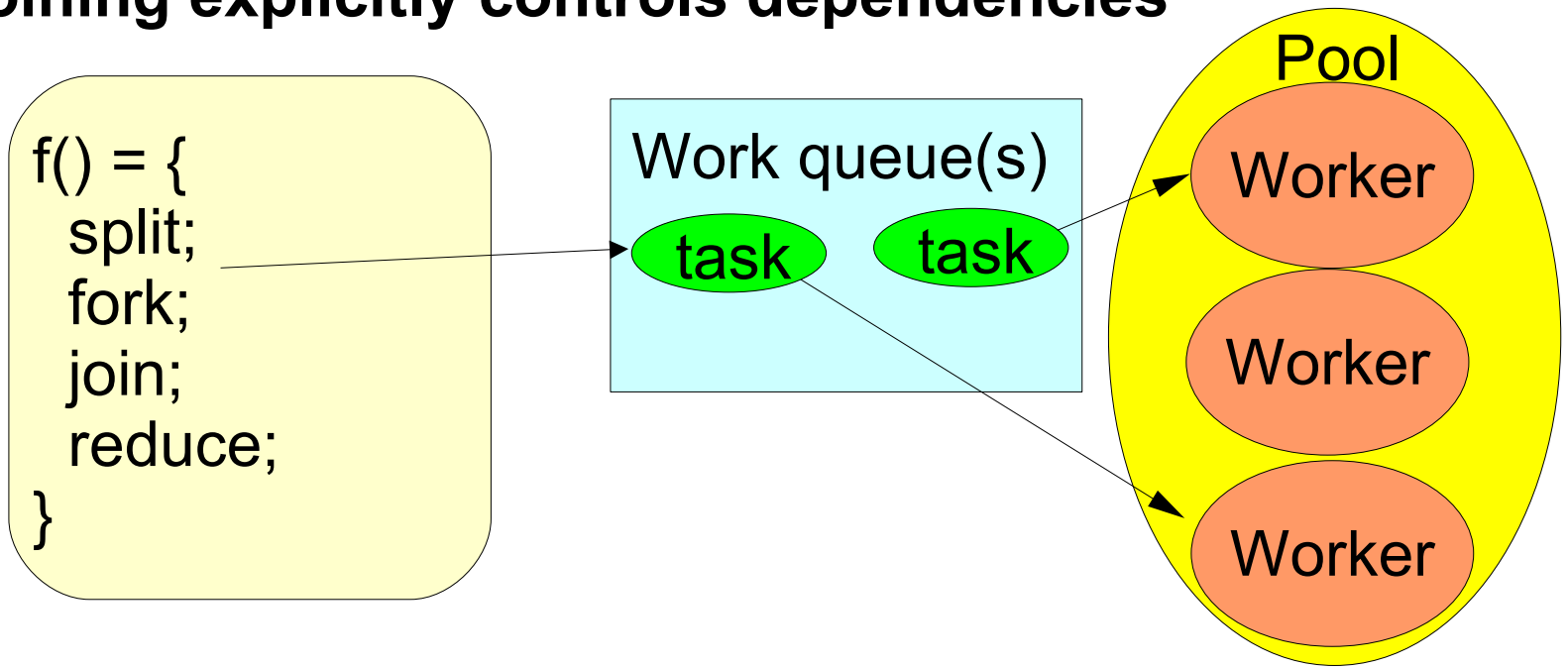
Multiprocessors and Multicores

- At least two new layers of parallelism
  - But coarser-grained
  - Split by instruction streams (threads)



Task-Based Parallel Evaluation

- Programs can be broken into tasks
  - Recursively; under some appropriate level of granularity
- Workers/Cores continually run tasks
  - Sub-computations are forked as subtask objects
- Sometimes need to wait for subtasks
  - Joining explicitly controls dependencies

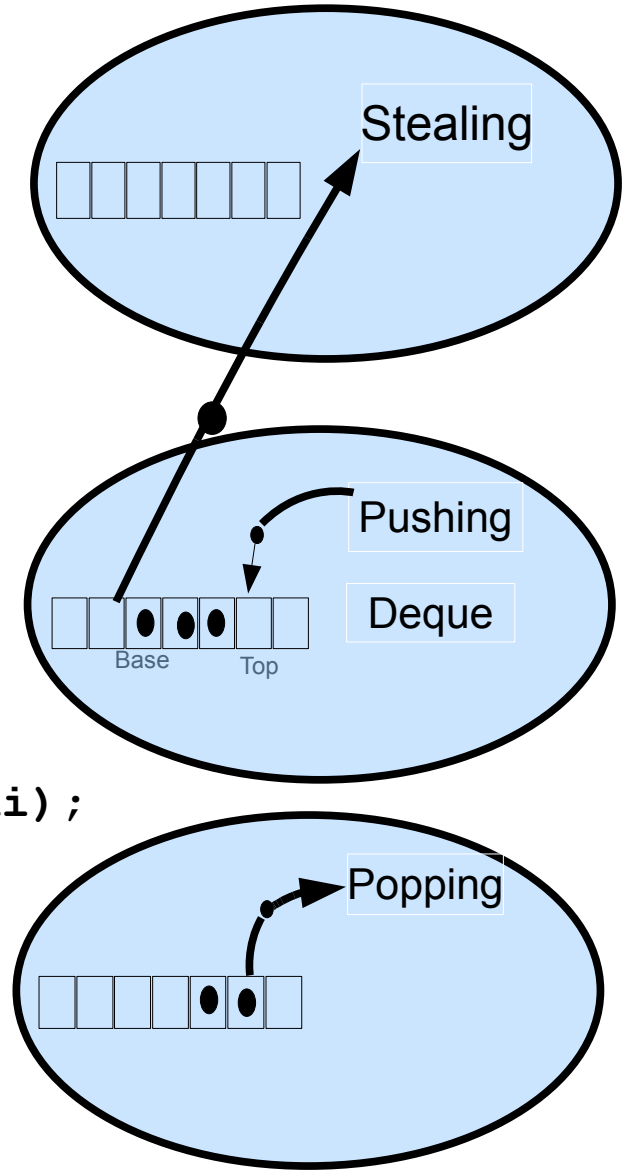


ForkJoin Sort (Java)

```
class SortTask extends RecursiveAction {
  final long[] array;
  final int lo; final int hi;

  SortTask(long[] array, int lo, int hi) {
    this.array = array;
    this.lo = lo; this.hi = hi;
  }

  protected void compute() {
    if (hi - lo < THRESHOLD)
      sequentiallySort(array, lo, hi);
    else {
      int m = (lo + hi) >>> 1;
      SortTask r = new SortTask(array, m, hi);
      r.fork();
      new SortTask(array, lo, m).compute();
      r.join();
      merge(array, lo, mid, hi);
    }
  }
    // …
} // (In Java, since no standard Scala APIs yet.)
```



Implementing ForkJoin Tasks

Queuing: Work-stealing

- Each worker forks to own deque; but steals from others or accepts new submission when no work

Scheduling: Locally LIFO, random-steals FIFO

- Cilk-style: Optimal for divide-and-conquer
- Ignores locality: Cannot tell if better to use another core on same processor, or a different processor

Joining: Helping and/or pseudo-continuations

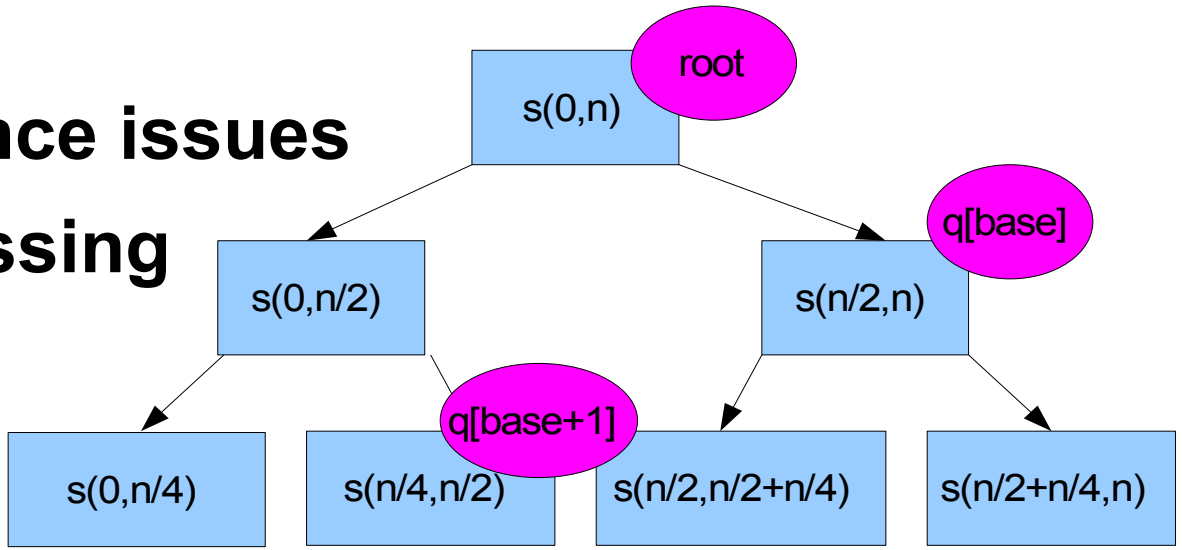
- Try to steal a child of stolen task; if none, block but (re)start a spare thread to maintain parallelism

Overhead: Task object with one 32-bit int status

- Payoff after ~100-1000 instructions per task body

Bulk Operations

- SIMD: Apply an operation to all elements of a collection
  - Procedures: Color all my squares red
  - Mappings: Map these student IDs to their grades
  - Reductions: Calculate the sum of these numbers
- A special case of basic parallel evaluation
  - Any number of components; same operation on each
  - Same independence issues
- Can arrange processing in task trees/dags
  - Array Sum:



Supporting Bulk Operations

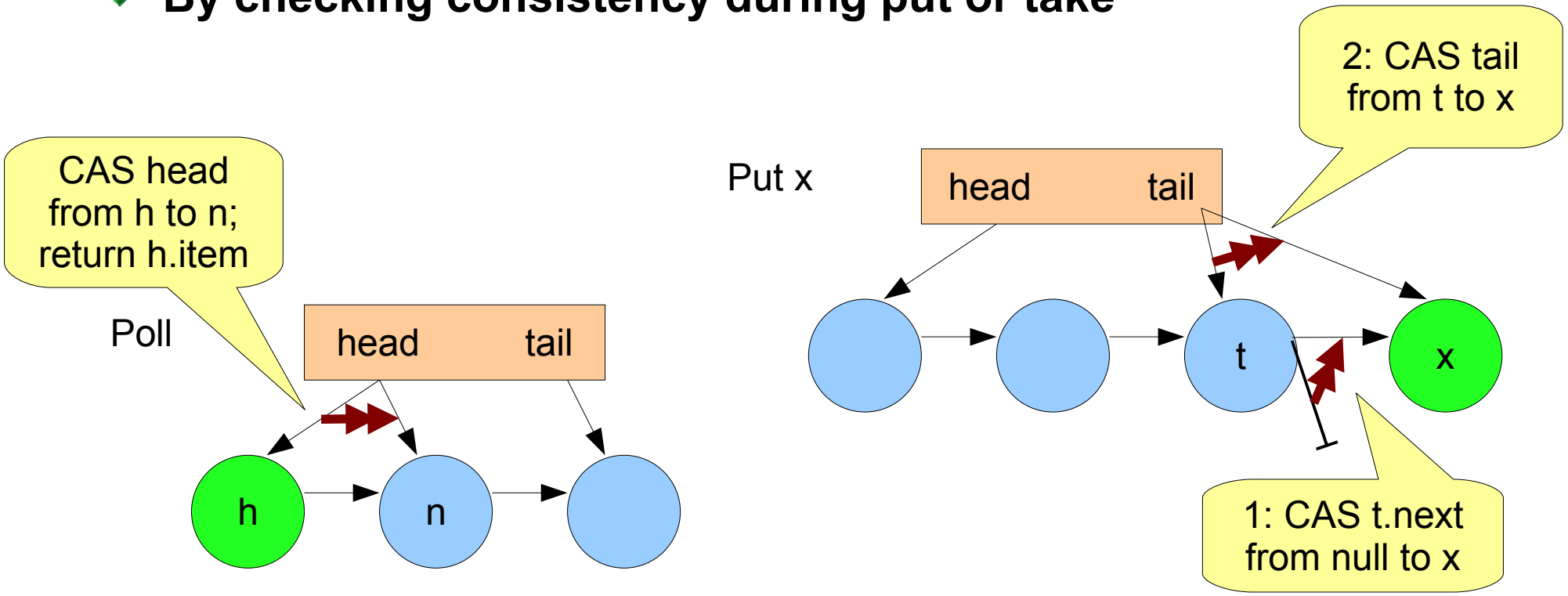
- Familiar APIs and usages: map, reduce/fold, filter,...
  - Common in many styles of programming
    - Requires use of closures to express ops
    - (See other talks for Scala details)
  - But some unfamiliar twists
    - Avoid sequential iterators, head::tail, etc
  - Functional style more readily optimizable
    - Ex: filter(p1).filter(p2) → filter(p1 & p2)
- Many ways to implement
  - Possibly via: SIMD instructions, GPUs, FPGAs, ForkJoin, Clusters (Hadoop etc)
    - But not even close to automating selection yet.

Semi-Transactional ADTs

- Explicitly concurrent objects used as resources
  - Support conventional APIs (Collections, Maps)
    - Examples: Registries, directories, message queues
  - Programmed in low-level JVMese – compareAndSet (CAS)
    - Often vastly more efficient than alternatives
- Roots in ADTs and Transactions
  - ADT: Opaque, self-contained, limited extensibility
  - Transactional: All-or-nothing methods
- Atomicity limits; e.g., no transactional removeAll
  - But can support *non*-transactional bulk *parallel* ops
    - (Need for transactional parallel bulk ops is unclear)
  - Possibly only transiently concurrent
    - Example: Shared outputs for bulk parallel operations

Example: Non-blocking Queues

- **Michael & Scott Queue (PODC 1996)**
  - **Use retriable CAS (not lock)**
  - **CASes on different vars (head, tail) for put vs poll**
  - **If CAS of tail from t to x on put fails, others try to help**
    - **By checking consistency during put or take**



Concurrent Collections

- Non-blocking data structures rely on simplest form of hardware transactions
  - CAS (or LL/SC) tries to commit a single variable
  - Frameworks layered on CAS-based data structures can be used to support larger-grained transactions
  - HTM (or multiple-variable CAS) would be nicer
    - But not a magic bullet
- Evade most hard issues in general transactions
  - Contention, overhead, space bloat, side-effect rollback, etc
  - But special cases of these issues still present
    - Complicates implementation: Hard to see Michael & Scott algorithm hiding in LinkedTransferQueue

Contention in Shared Data Structures

Mostly-Write

- Most producer-consumer exchanges
  - Especially queues
- Apply combinations of a small set of ideas
  - Use non-blocking sync via compareAndSet (CAS)
  - Reduce point-wise contention
  - Arrange that threads help each other make progress

Mostly-Read

- Most Maps & Sets
  - Empirically, 85% Java Map calls read-only
- Structure to maximize concurrent readability
  - Without locking, readers see legal (ideally, linearizable) values
  - Often, using immutable copy-on-write internals
  - Apply write-contention techniques from there

Objects, Actors, Messages, Events

- Reactive GUI, Web, embedded, etc applications
  - Almost necessarily object-oriented
- Many choices for semantics
  - Allow both actors and passive objects?
  - One actor (aka, the event loop) vs many?
  - Single- vs multi- threaded vs transactional actors?
  - Isolated (process-like) vs shared memory?
  - Explicitly remote vs local actors?
  - Point-to-point messaging vs multicast events?
  - Synchronous vs asynchronous messaging?
  - Support exceptions and Faults?
- JVM and libraries supply mechanism, not policy

Common Infrastructure

- Lightweight Actors
  - Similar (and can be identical) to lightweight Tasks
  - Multiplex to threads/processes/cores/hosts
    - Normally via Executor API
- Shared-memory sync support
  - Queues, Futures, Locks, Barriers, etc
  - Shared is faster than unshared messaging
    - But can be less scalable for point-to-point
  - Provides stronger guarantees: Cache coherence
  - Can be more error-prone: Aliasing, races, visibility
  - Exposing benefits vs complexity is policy issue

Events and Consistency

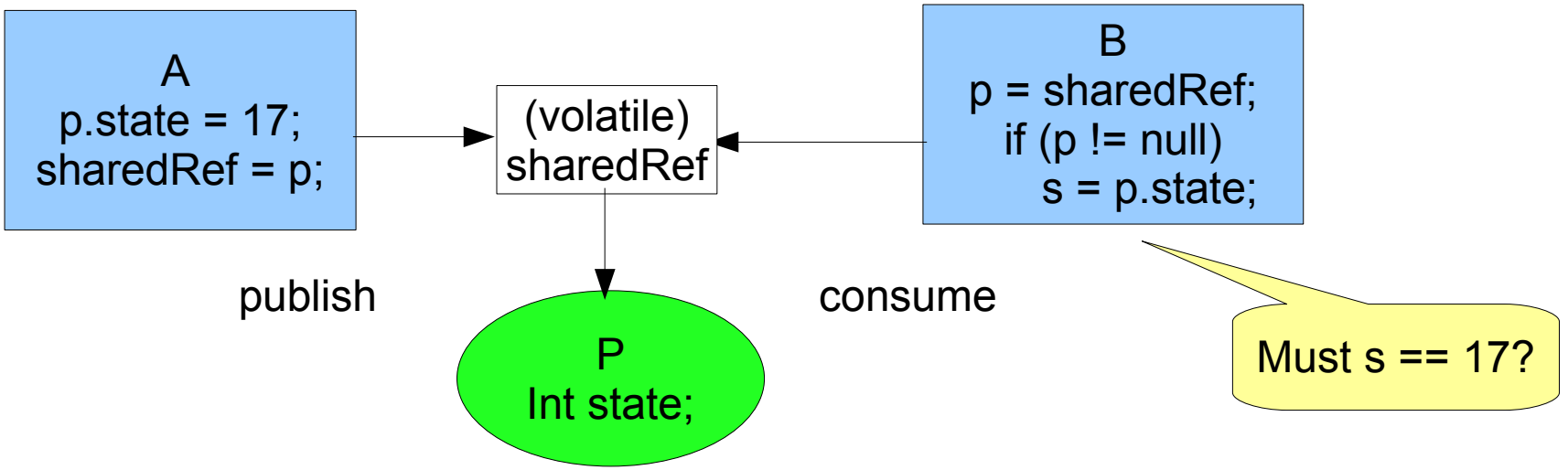
- Consistency issues are intrinsic to event systems
  - Example: vars x,y initially 0 → events x, y unseen
    - Node A: send x = 1; // (multicast send)
    - Node B: send y = 1;
    - Node C: receive x; receive y; // see x=1, y=0
    - Node D: receive y; receive x; // see y=1, x=0
- On shared memory, can guarantee agreement
  - JMM: declare x, y as volatile
- Remote consistency is expensive
  - Atomic multicast, distributed transactions; failure models
- Usually, weaker consistency is good enough
  - Example: Per-producer FIFO

Memory Models

- Distinguish sync *accesses* (locks, volatiles, atomics) from normal accesses (reads, writes)
- Require strong ordering properties among sync
  - Usually “strong” means Sequentially Consistent
- Allow as-if-sequential reorderings among normal
  - Usually means: obey seq data/control dependencies
- Restrict reorderings between sync vs normal
  - Rules usually not obvious or intuitive
  - Special rules for cases like final fields
- There's probably a better way to go about all this

Example: Ownership Transfer

- When B gains access to object P, it expects to see the state of P left by A that provided access.
  - Concurrent languages provide some means to express this (e.g., Java volatiles and atomics)
  - All j.u.c components guarantee safe transfer when applicable, so users never need to think about it.



Conclusions

- **Parallelism is everywhere**
  - Can be natural and elegant
  - Can be mind-numbingly messy and complex
  - Usually somewhere in-between
  - Just like every other aspect of programming
- **Diversity is essential**
  - Functional, OO, ADT styles all apply often
  - Language/library support for each continue to evolve
    - Encapsulate messiness; reduce complexity
  - Just like every other aspect of programming

Josh Bloch's version of this slide:
"*Life's a bitch, but the puppies are cute*"