Parallelism From The Middle Out

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The Middle Path to Parallel Programming

- Bottom up: Make computers faster via parallelism
  - Instruction-level, multicore, GPU, hw-transactions, etc
    - Initially rely on non-portable techniques to program
- Top down: Establish a model of parallel execution
  - Create syntax, compilation techniques, etc
  - Many models are available!
- Middle out: Encapsulate most of the work needed to solve particular parallel programming problems
  - Create reusable APIs (classes, modules, frameworks)
    - Have both hardware-based and language-based dependencies
  - Abstraction á la carte

The customer is always right?

- Vastly more usage of parallel library components than of languages primarily targeting parallelism
  - Java, MPI, pthreads, Scala, C#, Hadoop, etc libraries
- Probably not solely due to inertia
  - Using languages *seems* simpler than using libraries
  - But sometimes is not, for some audiences
- In part because language/library borderlines are increasingly fuzzy
  - Distinctions of categories of support across …
    - Parallel (high throughput)
    - Concurrent (low latency)
    - Distributed (fault tolerance)

… also becoming fuzzier, with many in-betweens.

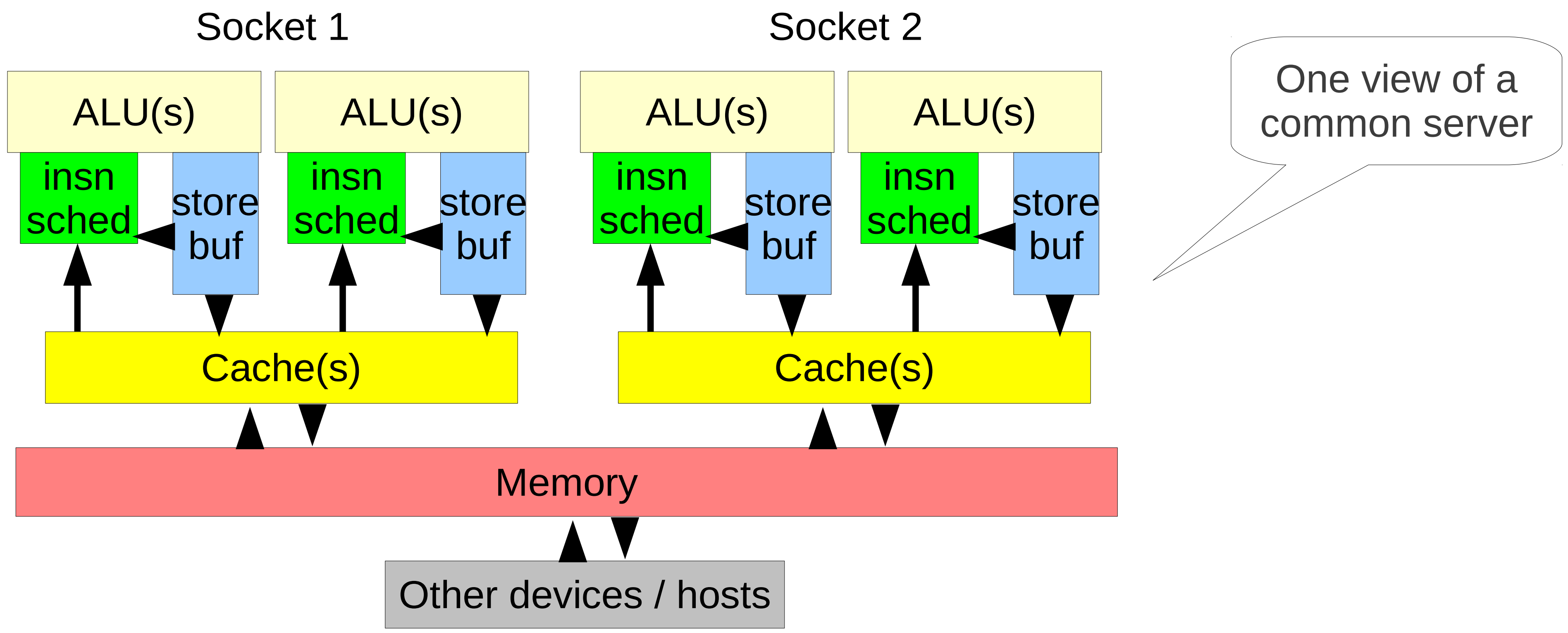
Theme: Abstractions vs Policies

- Hardware parallelism is highly opportunistic
    - Directly programming not usually productive
- Effective parallel programming is too diverse to be constrained by language-based policies
    - e.g., CSP, transactionality, side-effect-freedom, isolation, sequential consistency, determinism, …
        - But they may be helpful constraints in some programs
- Engineering tradeoffs lead to medium-grained abstractions
    - Still rising from the Stone Age of parallel programming
- Need diverse language support for expressing and composing them
    - Old news (Fortress, Scala, etc) but still many open issues

Hardware Trends

Opportunistically parallelize anything and everything

- **More gates → More parallel computation**
  - **Dedicated functional units, multicores**
- **More communication → More asynchrony**
  - **Async (out-of-order) instructions, memory, & IO**

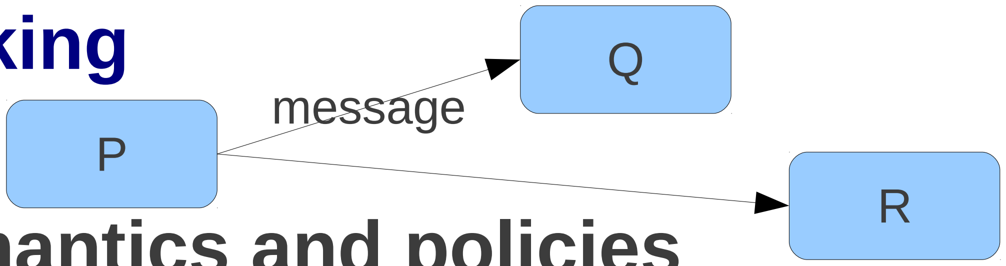


Parallelism in Components

- Over forty years of parallelism and asynchrony inside commodity platform software components
  - Operating Systems, Middleware, VMs, Runtimes
    - Overlapped IO, device control, interrupts, schedulers
    - Event/GUI handlers, network/distributed messaging
    - Concurrent garbage collection and VM services
  - Numerics, Graphics, Media
    - Custom hw-supported libraries for HPC etc
- Result in better throughput and/or latency
  - But point-wise, quirky; no grand plan
  - Complex performance models. Sometimes *very* complex
- Can no longer hide techniques behind opaque walls
  - Everyday programs now use the same ideas

Processes, Actors, Messages, Events

Deceptively simple-looking



- Many choices for semantics and policies
  - Allow both actors and passive objects?
    - Single- vs multi- threaded vs transactional actors?
    - One actor (aka, the event loop) vs many?
  - Isolated vs shared memory? In-between scopes?
    - Explicitly remote vs local actors?
  - Distinguish channels from mailboxes?
    - Message formats? Content restrictions? Marshalling rules?
  - Synchronous vs asynchronous messaging?
  - Point-to-point messaging vs multicast events?
    - Consensus policies for multicast events?
  - Exception, Timeout, and Fault protocols and recovery?

Process Abstractions

- **Top-down:** create model+language (ex: **CSP+Occam**) supporting a small set of semantics and policies
  - Good for program analysis, uniformity of use, nice syntax
  - Not so good for solving some engineering problems
- **Middle-Out:** supply policy-neutral components
  - Start with the Universal Turing Machine vs TM ploy
    - **Tasks** – executable objects
    - **Executors** – run (multiplex/schedule) tasks on cores etc
    - Specializations/implementations may have little in common
  - Add synchronizers to support messaging & coordination
    - Many forms of **atomics, queues, locks, barriers**, etc
  - Layered frameworks, DSLs, tools can support sweet-spots
    - e.g., Web service frameworks, Scala/akka actors
    - Other choices can remain available (or not) from higher layers

Libraries Focus on Tradeoffs

Library APIs are platform features with:

- Restricted functionality
  - Must be expressible in base language (or via cheats)
  - Tension between efficiency and portability
- Restricted scopes of use
  - Tension between Over- vs Under- abstraction
    - Usually leads to support for many styles of use
    - Rarely leads to sets of completely orthogonal constructs
      - Over time, tends to identify useful (big & small) abstractions
- Restricted forms of use
  - Must be composable using other language mechanisms
  - Restricted usage syntax (less so in Fortress, Scala, ...)
    - Tensions: economy of expression, readability, functionality

Composition

Components require language composition support

- APIs often reflect how they are meant to be composed

- To a first approximation, just mix existing ideas:
  - Resource-based composition using OO or ADT mechanics
    - e.g., create and use a shared registry, execution framework, ...
  - Process composition using Actor, CSP, etc mechanics
    - e.g., messages/events among producers and consumers
  - Data-parallel composition using FP mechanics
    - e.g., bulk operations on aggregates: map, reduce, filter, ...
- The first approximation doesn't survive long
  - Supporting multiple algorithms, semantics, and policies forces interactions
    - Requires integrated support across approaches

Data-Parallel Composition

Tiny map-reduce example: sum of squares on array

- Familiar sequential code/compilation/execution

```
 s = 0; for (i=0; i<n; ++i) s += sqr(a[i]); return s;
```

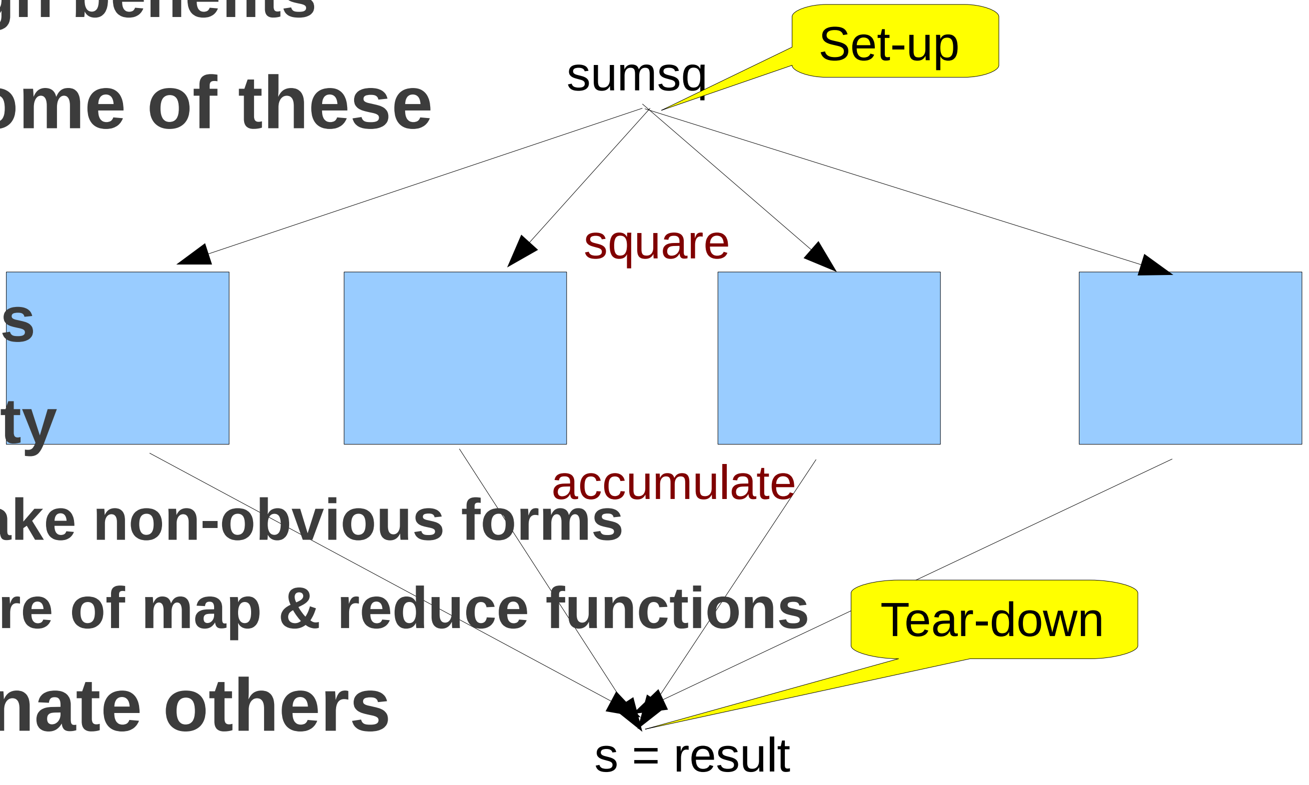
... or ...

```
reduce(map(a, sqr), plus, 0);
```

  - May be superscalar even without explicit parallelism
- Parallel needs algorithm/policy selection, including:
  - Split work: Static? Dynamic? Affine? Race-checked?
  - Granularity: #cores vs task overhead vs memory/locality
  - Reduction: Tree joins? Async completions?
  - Substrate: Multicore? GPU? FPGA? Cluster?
- Results in families of code skeletons
  - Some of them are even faster than sequential

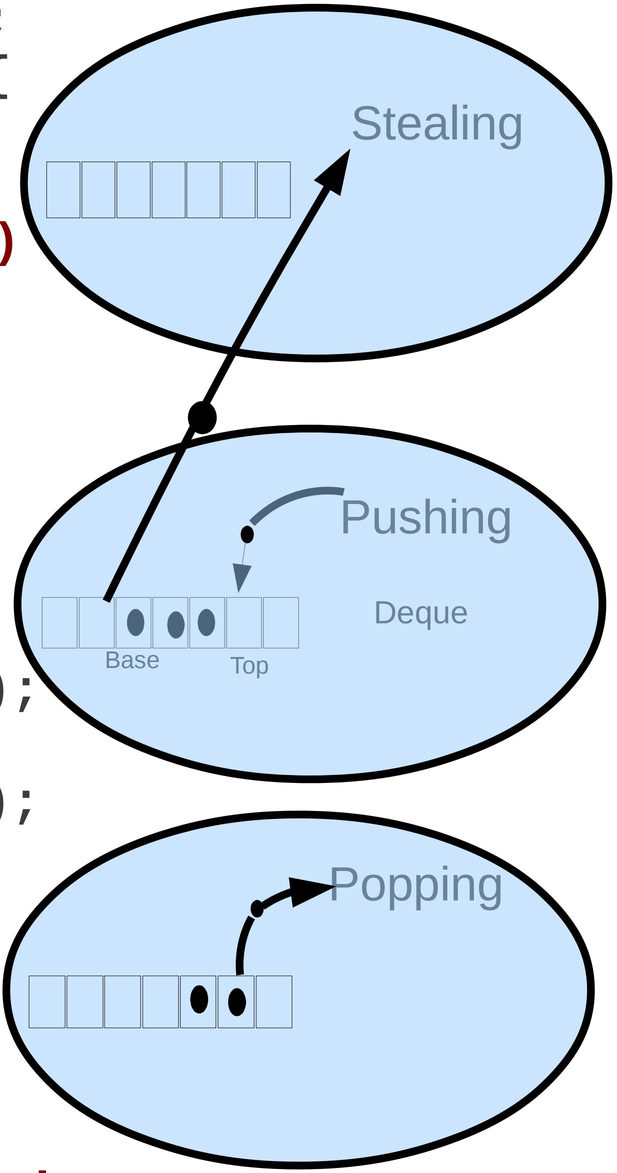
Bulk Operations and Amdahl's Law

- Sequential set-up/tear-down limits speedup
  - Or as lost parallelism = (cost of seq steps) * #cores
  - Can easily outweigh benefits
- Can parallelize some of these
  - Recursive forks
  - Async Completions
  - Adaptive granularity
    - Best techniques take non-obvious forms
    - Some rely on nature of map & reduce functions
- Cheapen or eliminate others
  - Static optimization
    - Jamming/fusing across operations; locality enhancements
  - Share (concurrent) collections to avoid copy / merge



Sample ForkJoin Sum Task

```
class SumSqTask extends RecursiveAction {
  final long[] a; final int l, h; long sum;
  SumSqTask(long[] array, int lo, int hi) {
    a = array; l = lo; h = hi;
  }
  // (One basic form; many improvements possible)
  protected void compute() {
    if (h - l < THRESHOLD) {
      for (int i = l; i < h; ++i)
        sum += a[i] * a[i];
    }
    else {
      int m = (l + h) >>> 1;
      SumSqTask rt = new SumSqTask(a, m, h);
      rt.fork(); // pushes task
      SumSqTask lt = new SumSqTask(a, l, m);
      lt.compute();
      rt.join(); // pops/runs or helps or waits
      sum = lt.sum + rt.sum;
    }
  }
}
```



Tediously similar code for many other bulk operations

Composition Using Injection

- Simplify data-parallelism by allowing injection of code snippets into holes in skeletons
  - Subject to further transformation/optimizations
  - Some users need to program the skeletons
    - Some only need to occasionally fine-tune them
  - Most users usually just want to supply the snippets
- Need to represent and manipulate code snippets
  - Closure-objects, lambdas, macros, templates, etc
    - Each choice has good and bad points
      - e.g., megamorphic dispatch vs code bloat
      - Easy to confuse the means and ends (**lambda != FP**)
  - Or push up one level and use generative IDE-based tools or layered languages
    - A long heritage for GUI, web page, etc composition of snippets

Composition on Shared Resources

- **Top-down:** Create a transactional (sub)language to support multi-operation, multi-object atomicity
  - Automate contention, space mgt, side-effect rollback, etc
  - So far, at best, highly variable performance
- **Library-based:** Provide Collections supporting finite sets of possibly-compound atomic operations
  - Example: ConcurrentHashMap.putIfAbsent
    - Key-value maps often the focus of transactions; cf SQL
    - Can be implemented efficiently
  - Improve atomic APIs based on experience
    - e.g., adding computeIfAbsent, recompute
      - Usually can only do so for implementations, not interfaces
  - Multi-object atomicity guarantees are missing or limited
    - Best bet: Support under composition constraints

Implementing Shared Data Structures

Mostly-Write

- Most producer-consumer exchanges
- Apply combinations of a small set of ideas:
  - Use non-blocking sync via compareAndSet (CAS)
    - Or hardware TM if available
  - Relax internal consistency requirements & invariants
  - Reduce point-wise contention
  - Arrange that threads help each other make progress

Mostly-Read

- Most Maps & Sets
- 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

Composition and Consistency

- Consistency policies are intrinsic to systems with multiple readers or multicast (so: part of API design)
- Most consistency properties do not compose
  - IRIW Example: vars x,y initially 0 → events x, y unseen
    - Activity A: send x = 1; // (multicast send)
    - Activity B: send y = 1;
    - Activity C: receive x; receive y; // see x=1, y=0
    - Activity D: receive y; receive x; // see y=1, x=0 ? Not if SC
- For vars, can guarantee sequential consistency
  - JMM: declare x, y as volatile
- Doesn't necessarily extend to component operations
  - e.g., if x, y are two maps, & the r/w operations are put/get(k)
- Doesn't extend at all under failures
  - Even for fault-tolerant systems (CAP theorem)

Documenting Consistency Properties

Example: ForkJoinTask.fork API spec

“Arranges to asynchronously execute this task. While it is not necessarily enforced, it is a usage error to fork a task more than once unless it has completed and been reinitialized. Subsequent modifications to the state of this task or any data it operates on are not necessarily consistently observable by any thread other than the one executing it unless preceded by a call to join() or related methods, or a call to isDone() returning true.”

- The no-refork rule ultimately reflects internal relaxed consistency mechanics based on ownership transfer
  - The mechanics leverage fact that refork before completion doesn't make sense anyway
- The inconsistent-until-join rule reflects arbitrary state of, e.g., the elements of an array while it is being sorted
  - Also enables weaker ordering (more parallelism) while running
- Would be nicer to statically enforce
  - Secretly, the no-refork rule cannot now be dynamically enforced

Determinism á la carte

- Common components entail algorithmic randomness
  - Hashing, skip lists, crypto, numerics, etc
    - Fun fact: The Mark I (1949) had hw random number generator
  - Visible effects; e.g., on collection traversal order
    - API specs do not promise deterministic traversal order
      - Bugs when users don't accommodate
  - Randomness more widespread in concurrent components
    - Adaptive contention reduction, work-stealing, etc
- Plus non-determinism from multiple threads
  - Visible effects interact with consistency policies
- Main problem across all cases is bug reproducibility
  - A design tradeoff across languages, libraries, and tools
  - Non-deterministic performance bugs exist independently

Usability of Abstractions

Users like and use some API styles more than others

- Futures: r = ex.submit(func); … ; use(r.get());
  - Idea: parallel variant of lazy evaluation
    - Nicely extend to recursive parallelism (j.u.c ForkJoinTasks)
  - Intuitive/pleasant even if need explicit syntax to get result
    - But can be a resource management problem when recursively blocked on indivisible leaf actions (like IO)
      - Chains of blocked threads; requires internal mgt heuristics
- Completions: t2 = new CC(1, t1); … t2.fork(); ...
  - Idea: arrange to trigger an action when other(s) complete
    - Atomic triggers for continuations avoid cascaded blocking
  - Often less intuitive/pleasant even with syntax support
    - Non-block-structured cases especially messy
    - Current j.u.c solution: Support with ugly API

Practical Pitfalls of Layering

Minimal support for building libraries...

- load/store ordering, atomics, start/block/unblock threads, ...

... doesn't always mean easy or pleasant support:

- Coping with *Idiot Savant* dynamic compilation/optimization
  - Manual dataflow optimization
  - Using intrinsics (pseudo-bytecodes)
- Interactions with VM bookkeeping and services
  - Coping with code between the lines (e.g., safepoints)
  - Coping with GC anomalies (e.g., floating garbage)
  - Indirectly influencing memory locality, memory contention
- Coping with processor, VM, OS, Hypervisor quirks/bugs
  - Avoiding fall-off-cliff costs (e.g., when blocking threads)
- And more. For some gory details, see upcoming SPAA talk

Software Process

- Incrementalism requires shorter cycles
  - Releasing a component easier than language or hardware
  - Users: Trying new library easier than new language
  - Continuous feedback on functionality, usability
- New APIs provide ideas for restructuring programs
  - Balancing with what users say they want
    - Some ideas don't make it into release
  - Also provide new user bug opportunities
    - Has led to new bug pattern detectors in findBugs
- Multiple audiences
  - Heaviest j.u.c. users use it to build layered frameworks
  - Users with better ideas can create better components

Summary: Themes revisited

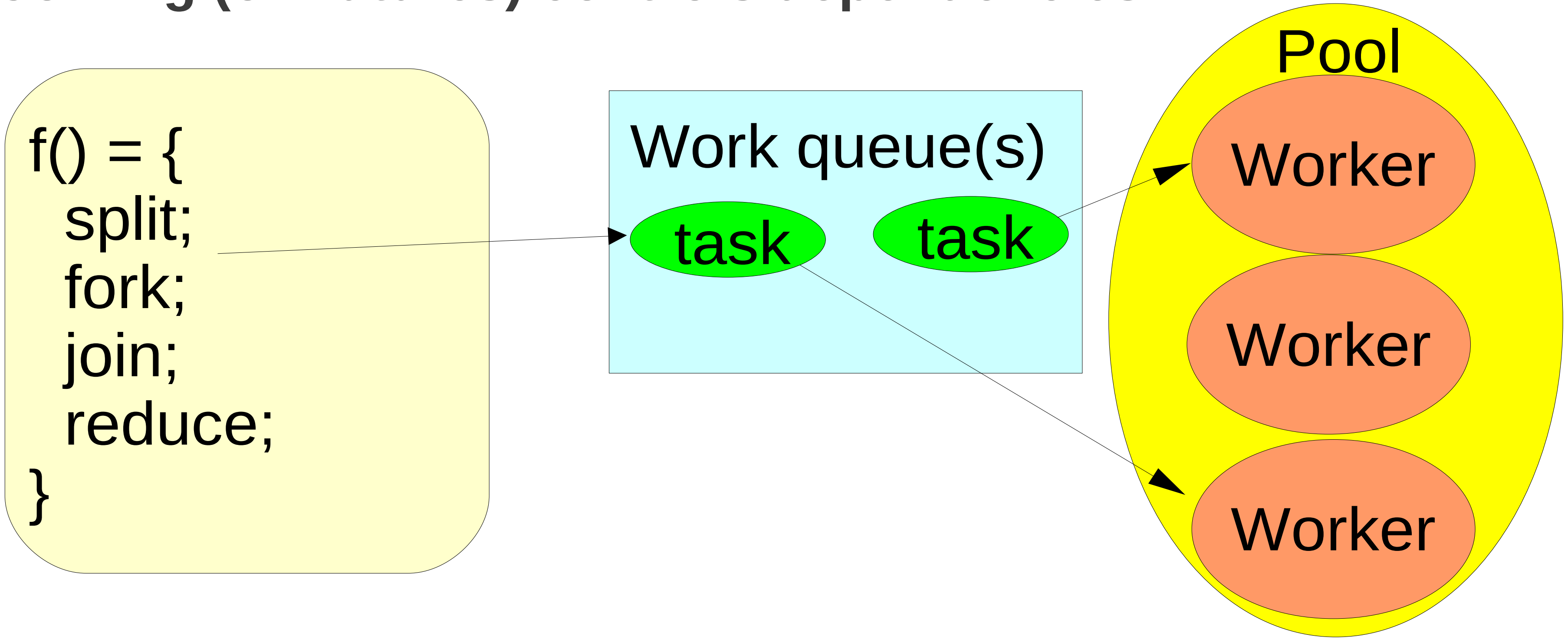
- Effective parallel programming is too diverse to be constrained by language-based policies
  - But often useful to layer policy over mechanism
    - For sake of learnability, static analysis, debugging, optimization
- Engineering tradeoffs lead to medium-grained abstractions
  - Incorporate ideas from many modes/styles
  - Common language design concerns are among tradeoffs
    - Orthogonality, generality, specification rigor, usability
  - May lead to multiple co-existing solutions
- Need diverse language support for expressing and composing them
  - Too few component developers can now cope

Backup slides

Backup slides follow

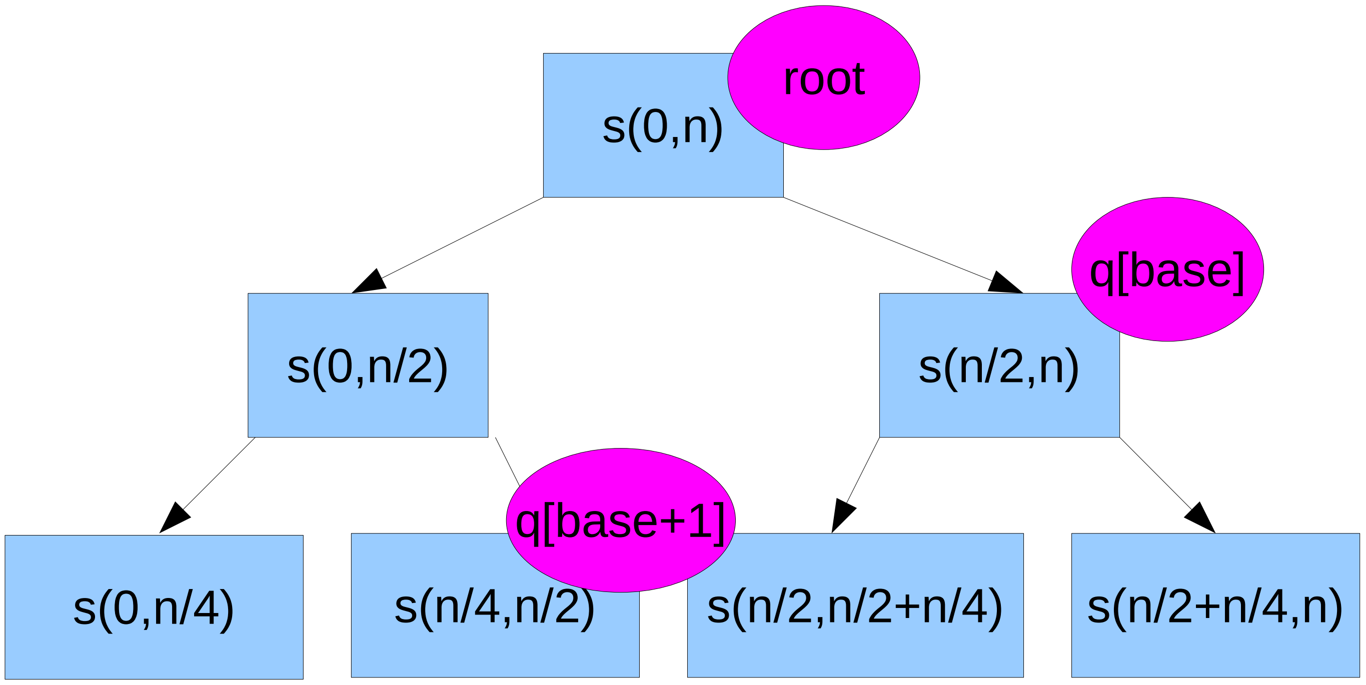
Task-Based Parallel Evaluation

- Programs can be broken into tasks
  - 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 (or Futures) controls dependencies



Computation Trees and Deques

- For recursive decomposition, deques arrange tasks with the most work to be stolen first. (See Blelloch et al for alternatives)
- Example: method s operating on array elems 0 ... n:



Parallel Recursive Decomposition

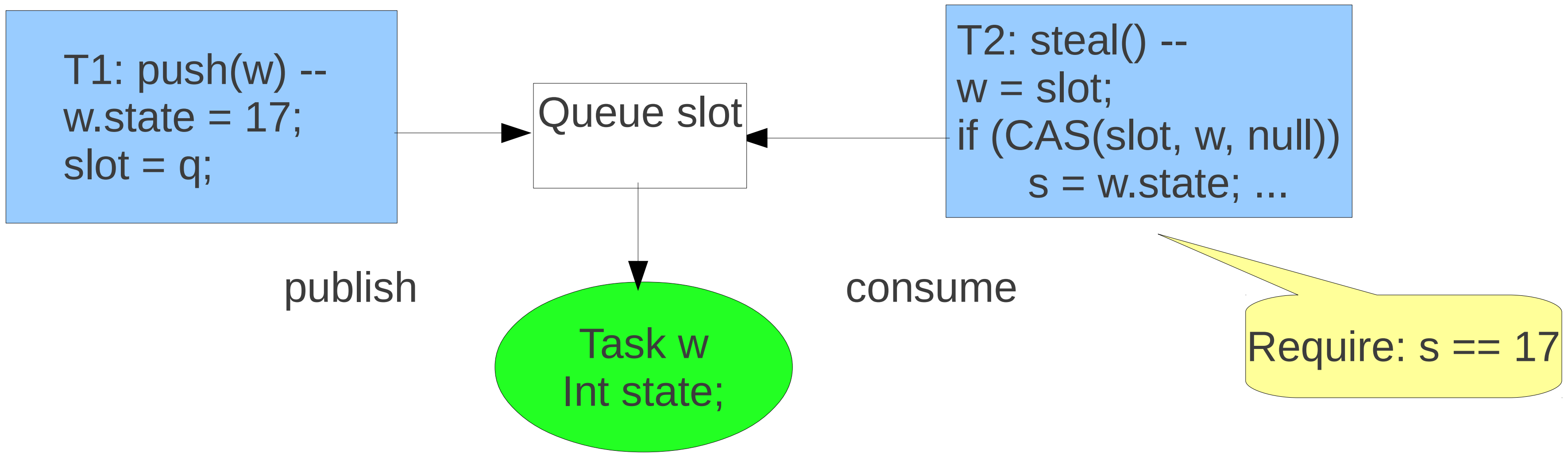
Typical algorithm

```
Result solve(Param problem) {
  if (problem.size <= THRESHOLD)
    return directlySolve(problem);
  else {
    in-parallel {
      Result l = solve(leftHalf(problem));
      Result r = solve(rightHalf(problem));
    }
    return combine(l, r);
  }
}
```

- To use FJ, must convert method to task object
  - “in-parallel” can translate to invokeAll(leftTask, rightTask)
- The algorithm itself drives the scheduling
- Many variants and extensions

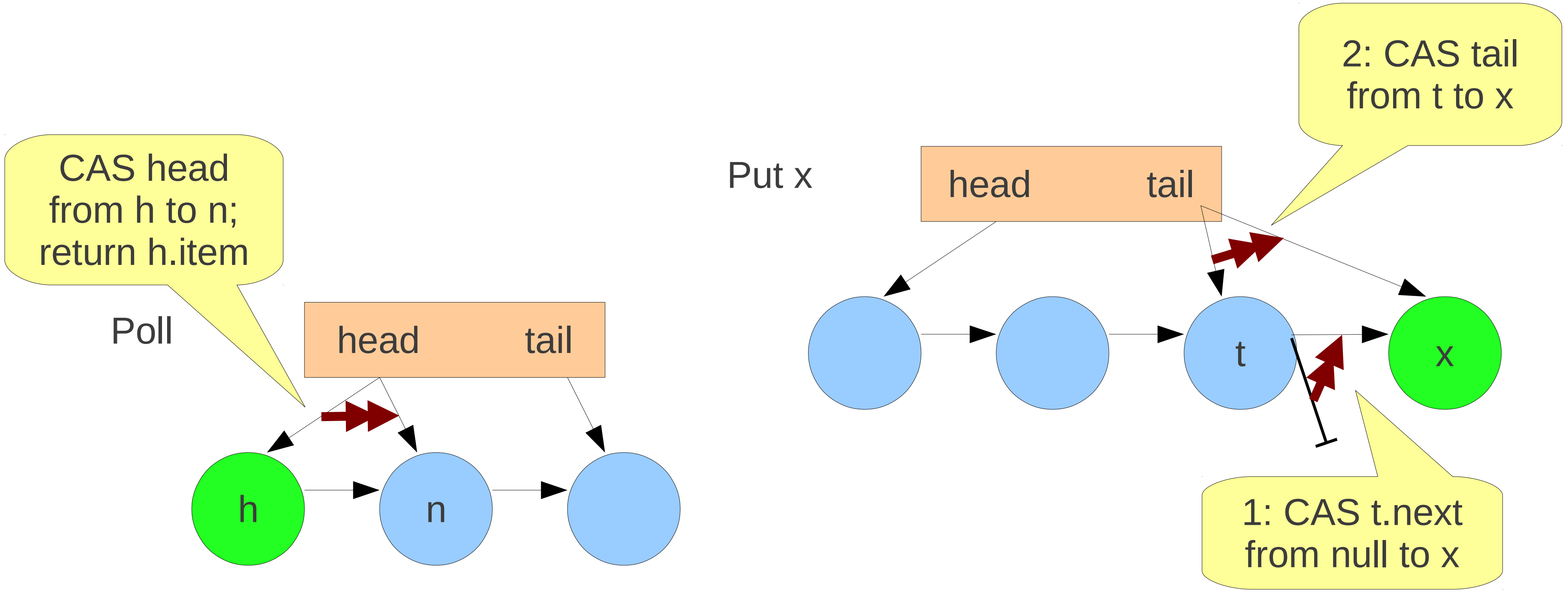
Transferring Tasks

- Queues perform a form of ownership transfer
  - Push: make task available for stealing or popping
    - needs lightweight store-fence
  - Pop, steal: make task unavailable to others, then run
    - Needs CAS with at least acquire-mode fence
- Java doesn't provide source-level map to efficient forms
  - So implementation uses JVM intrinsics


```
T1: push(w) --
w.state = 17;
slot = q;
```
```
T2: steal() --
w = slot;
if (CAS(slot, w, null))
    s = w.state; ...
```

ConcurrentLinkedQueue

- 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


CAS head from h to n; return h.item
Poll
head
tail
h
n
Put x
head
tail
t
x
2: CAS tail from t to x
1: CAS t.next from null to x