The State of Parallel Programming

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The von Neumann Premise

"Instructions are executed one at a time…"

- We have relied on this premise for about 60 years
- Now it (and some things it brought) must change
  - Serial language programs schedule values into variables
  - Parallel execution makes this scheme hazardous
- Serial programming is easier than parallel programming, at least at the moment
  - But serial programs are quickly becoming slow programs
- We need parallel programming paradigms that will make everyone who writes programs successful
- The stakes for our field's vitality are high

Programming must be reinvented

Parallel Programming Successes

- There have been two promising techniques:
  - Isolated memory updates
  - Functional programming
- Neither is completely satisfactory by itself
  - Isolated memory still needs communication and synchronization
  - Functional languages need parallel mutable state updates
- Data bases show the synergy between the two ideas
  - SQL is a “mostly functional” language
  - Transactions implement dynamic isolation of updates

Functional Programming

- Expressions on immutable values are scheduled and executed in dependence order
- There are language variants to suit any taste:
  - Strict or lenient or hybrids of these
  - Higher order functions or not
  - Declarative (*e.g.* comprehensions) or imperative
- Functional languages can also be efficient
  - Both Sisal and NESL competed well with Fortran on Crays
  - SQL and Excel can and do execute in parallel
- We must make our languages more functional
  - In doing so we must also make them more accessible

Maintaining Invariants

- Serial programming lets us perturb and then restore invariants in local (lexical) fashion
  - “Hoare Logic” depends on this property
  - It’s mostly automatic once we have learned to program
- State updates must be non-interfering
  - That is, they must be *isolated* in some fashion
  - Otherwise, “too many cooks” would spoil the dish
- *And* we must finish every update we start
  - lest the next update see the invariant false
  - Therefore the state updates must be *atomic*

Commutativity (AKA Determinism)

- If statements *p* and *q* preserve invariant $\mathscr{I}$ and do not "interfere", then their parallel composition { *p* || *q* } also preserves $\mathscr{I}$ †
- If *p* and *q* are performed *in isolation* and *atomically, i.e.* as *transactions*, then they will not interfere ‡
- Operations may not commute with respect to state
  - But we always get *commutativity with respect to the invariant*
- This leads to a weaker form of determinism
  - Long ago we called it "good nondeterminism"
  - It's the kind of determinism operating systems rely on

† Susan Owicki and David Gries. Verifying properties of parallel programs: An axiomatic approach. CACM **19**(5):279−285, May 1976.

‡ Leslie Lamport and Fred Schneider. The "Hoare Logic" of CSP, And All That. ACM TOPLAS **6**(2):281−296, Apr. 1984.

Implementing Isolation

- Analyzing
  - Proving concurrent updates are disjoint in space or time
- Locking
  - Meanwhile handling deadlock in some way
- Copying
  - Often used for wait-free updates
- Partitioning
  - The partitions can be dynamic
- Serializing

These schemes are often combined, *e.g.* serializing access to shared mutable state within each block of a partitioned memory

Implementing Atomicity

- Atomicity means "all or nothing" execution
  - If something goes wrong, all state changes must be undone
- Isolation without atomicity isn't worth much
  - But atomicity is usually crucial even in the serial case
- Techniques:
  - Deferring state changes until the atomic action "commits"
  - Logging, *i.e.* remembering and restoring original state values
  - Compensating, *i.e.* reversing the computation "in place"
- *Transactional Memory* means lexically scoped atomicity and isolation for arbitrary memory references
  - TM is a hot topic these days
- There is a lot of compiler optimization work ahead
  - to make atomicity and isolation as efficient as possible

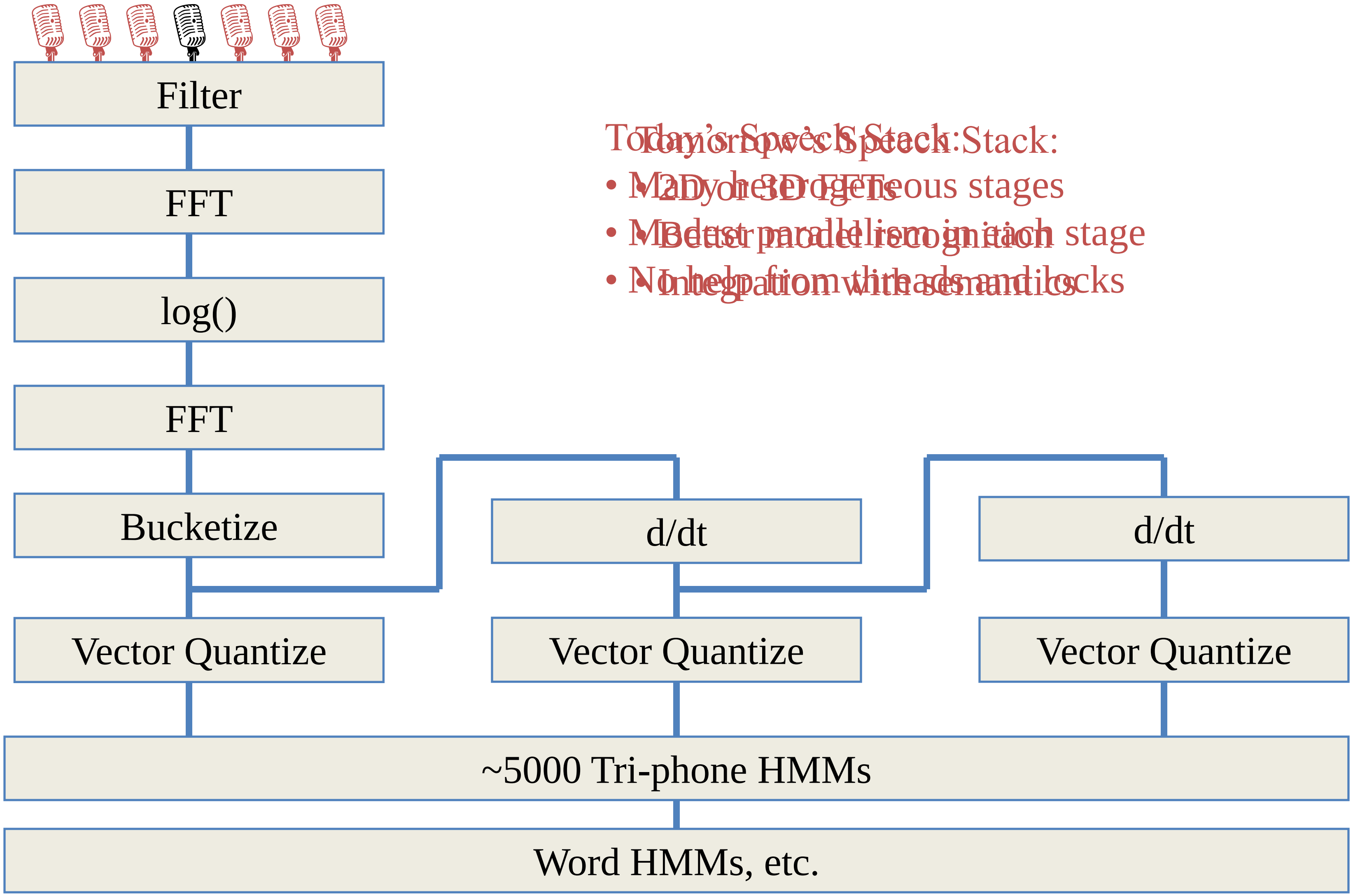
Styles of Parallelism

- We need to support a mix of programming ideas
  - A combination of functional and transactional styles
  - A combination of data and task parallelism
  - A combination of message passing and shared memory
  - A combination of declarative and imperative specification
  - A combination of implicit and explicit syntax
- We may need several languages to accomplish this
  - After all, we use multiple languages today
  - Language interoperability (e.g. via .NET) will help greatly
- Parallelism and locality must be abstract but visible
  - So that compilers can adapt code to many target systems

Implementing Parallelism

- Exploitable parallelism grows as task granularity shrinks
  - But dependences among tasks become more numerous
- Dependence enforcement needs blocking synchronization
  - A task needing a value from another must wait for it
- Today's OSes and hardware don't encourage blocking
  - OS thread preemption, *etc.* makes blocking dangerous
  - Instruction sets also encourage non-blocking behavior
- User-level work scheduling and synchronization are needed
  - No privilege change to stop or restart a subcomputation
  - Locality (*e.g.* cache content) can be better preserved

A Fine-Grain Example: Speech



Today's Speech Stack:
- Many heterogeneous stages
- Modest parallelism in each stage
- No help from threads and locks

Tomorrow's Speech Stack:
- 2D or 3D FFTs
- Better model recognition
- Integration with semantics

Synchronizing Streaming

- Streaming in parallel needs *producer-consumer* synchronization
  - Barriers wind up serializing the stages
- Basically, this implies FIFOs in memory
- One-item FIFOs are especially useful
  - This is just “full/empty bit” synchronization
  - We can avoid adding extra bits to existing hardware
- Producers and consumers can share caches
  - Both bandwidth and latency are thereby improved

Parallel Debugging and Tuning

- Today, debugging relies on single-stepping and `printf()`
  - Single-stepping a parallel program is much less effective
- Conditional program and data breakpoints are helpful
  - To stop when an invariant fails to be true
- Support for ad-hoc data perusal is also very important
  - Debugging is a form of data mining
- Serial program tuning tries to discover where the program counter spends its time
  - The answer is usually found by sampling the PC
- In contrast, parallel program tuning tries to discover where there is insufficient parallelism
  - A good way is to log resource consumption counters and a system-consistent timestamp at the key events
- Visualization is a big deal for both debugging and tuning

Conclusions

- We must now rethink the basics of programming
- There is interesting work for everyone
- New opportunities are likely to emerge