Programming Languages for HPC

Is There Life After MPI?

Marc Snir

HPCS Assumptions

- HPC is hampered by lack of good programming language support
- In particular, the use of MPI leads to low software productivity
- Problem can be resolved by doing research on new programming languages

Paradigm Shifts

- New languages/models succeed only if they enable new capabilities.
  - In HPC, the drive has always been the need to exploit the performance of a new computer architecture: shift to vector, next to MPP
- Obstacles to the introduction of new languages are higher today than 20 years ago
  - Weight of existing software
  - Investment needed to create good compilers and good ADE’s.

Productivity Wall?

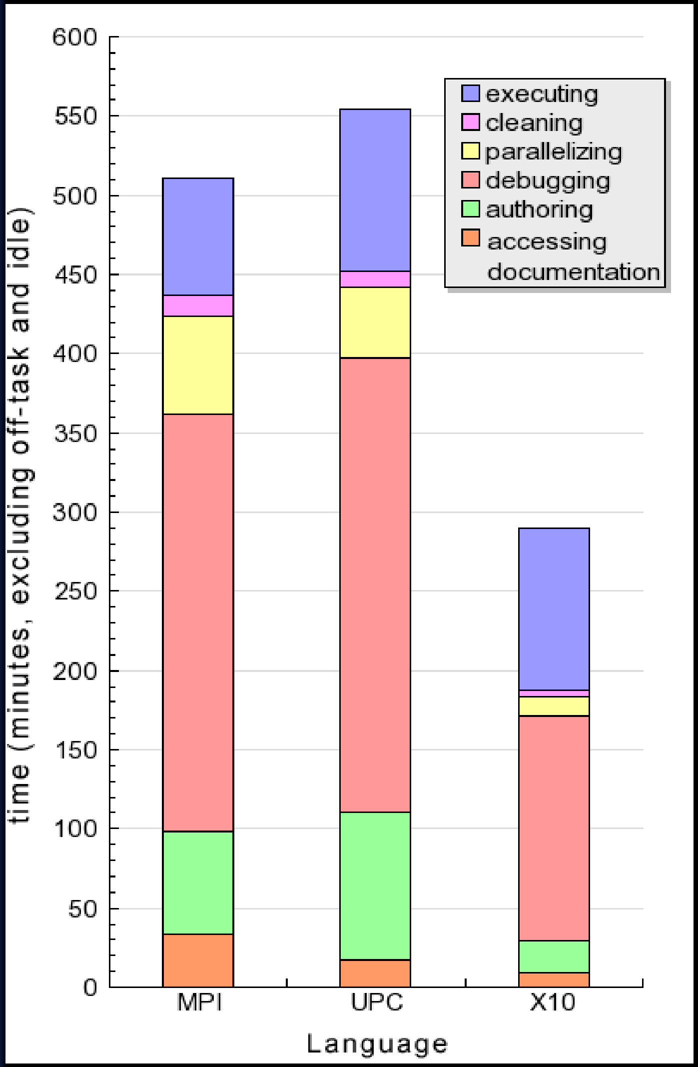


Chart: Courtesy of IBM

- Better language reduces programming time in some experiments (for non-expert programmers and short programs)
- Effect is probably small for large programs using OOP and for expert programmers
- Advantage may be reduced or negated if performance tuning is taken into account

Performance Wall (circa 2020) Extrapolation of current Trends

- Single chip performance:
  - Memory wall: a processor chip executes ~ 100Kflop/s in the time needed to satisfy one load; need ~ 750 pending loads at anytime.
  - Heterogeneity: deep memory hierarchy and multiple forms of parallelism on chip
- "Everybody" has to face these problems.
  - Programming models that palliate these problems will come as a result of broad market need
  - But HPC community faces them earlier... (low cache utilization, compute intensive codes)

Performance Wall (circa 2020) (continued)

- Large System Issues:
  - Global latency: 200 nsec = 0.7 Mflop/s
  - Efficient use of machines with > billion of concurrent operations
    - True, whether one uses many “light nodes” or fewer “heavy nodes”
  - Reliability
    - Problem for any large systems but harder for large, tightly coupled computations
  - Jitter, due to hardware, software or application

New Language has a Chance

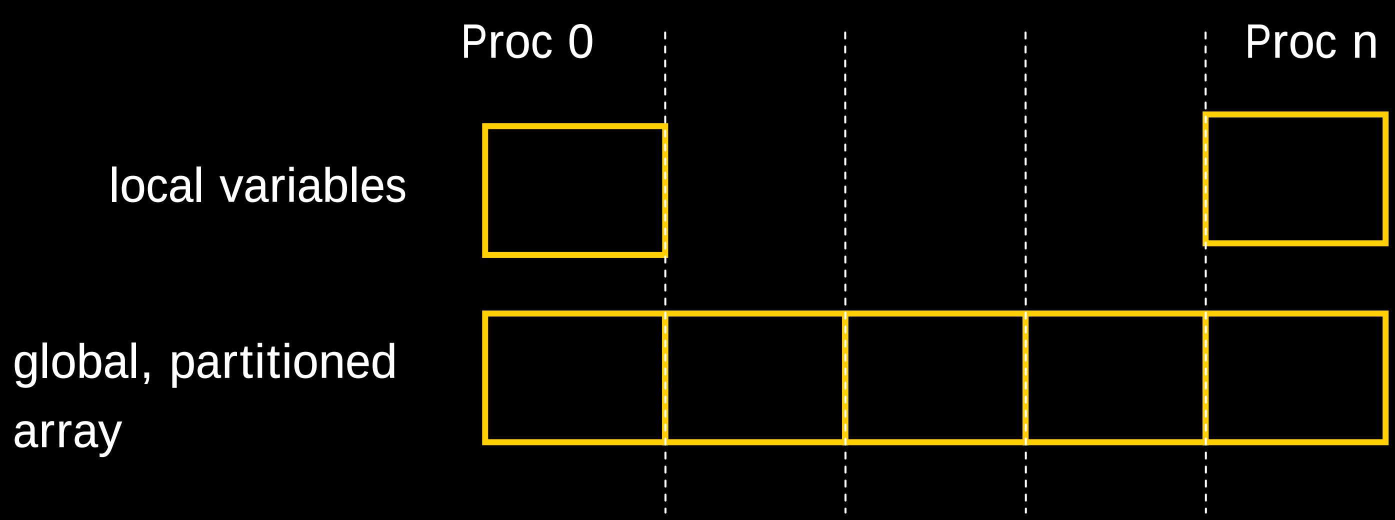
- New language needed, not for software productivity, but for performance at Petascale.
- While we are at it, we may also improve software productivity

What a New Language Should Do

- Address performance issues of large future systems
- Express well common HPC programming patterns
- Support well performance programming, with incremental code refinement
- Support OO
- Take advantage of advances in PL's: strong typing, type and memory safety, atomicity, efficient support for generic programming
- Take advantage of advances in compilers: dynamic compilation, heuristic search, telescoping languages
- Coexist with existing languages
- Provide state of the art ADE
  - Largely built on language with large market

PGAS Languages
Partitioned Global Address Space

- Fixed number of processes, each with one thread of control
- Global partitioned arrays that can be accessed by all processes
  - Global arrays are syntactically distinct from local variables
  - Compiler generates communication code for each access
- Limited number of global synchronization calls



- CAF (Fortran) , UPC (C), Titanium (Java)

Co-Array Fortran

- Global array ≡ one extra dimension
  - integer a[*] - one copy of a on each process
  - real b(10)[*] - one copy of b(10) on each process
  - real c(10)[3,*] – one copy of c(10) on each process; processes indexed as 2D array
- SPMD
  - code executed by each process independently
  - communication by accesses to global arrays
  - split barrier synchronization

notify_team(team)   sync_team(team)

Unified Parallel C

- (Static) global array is declared with qualifier shared
  - shared int q[100] – array of size 100 distributed round-robin
  - shared [*] int q[100] – block distribution
  - shared [3] int q[100] – block-cyclic distribution
  - shared int* q – local pointer to shared
- SPMD model
  - code executed by each process independently
  - communication by accesses to global arrays
    - global barrier or global split barrier
    - upc_barrier, upc_notify, upc_wait
  - simple upc_forall: each iteration is executed on process specified by affinity expression

X10 (IBM)

- Based on Java
- Fixed number of places
  - places could migrate
- Each datum has one fixed place
  - arrays can be distributed
- Each place supports variable number of threads
  - thread can be spawned on locale
- Remote data can be accessed or updated only by spawning asynchronously remote activities (which may return a value – future)
- Synchronization constructs: “finish”, atomic sections and clocks

Chapel (Cray)

- Not based on existing language, but supports OO, and generic programming
- Data is distributed over “locales” – fixed location
  - Can add cache protocol (?)
- Mostly data parallelism
  - Array expressions
  - generalized forall
- Cobegin for parallel blocks
- Execution location may be controlled (in foralls and parallel blocks) via “on” expression
- Each thread can touch any variable
  - Weak memory consistency model
- Support for atomic sections
- Support for parallel reductions

Fortress (Sun)

- Not based on existing language
  - Safety features of Java, support for OO and generic programming, "math-like" syntax, support for vectors, matrices, etc.
- Shared global address space
- Loops are parallel by default
- data and loop iterates are distributed
  - distribution is defined by type with a distribution policy defined by a type-associated library (standard or user defined)
- Support for atomic sections
- Language is extendible via libraries that have syntactic and semantic compiler support (telescoping languages, Rose...)

Fortress Syntax

ASCII	UNICODE	Two-dimensional
`rho0 = r DOT r`	ρ_0 `= r·r`	$\rho_0 = r \cdot r$
`v_norm = v / norm v`	`v_norm = v / ‖v‖`	$v_{norm} = \frac{v}{\lVert v \rVert}$
`SUM[k=1:n] a[k] x^k`	`Σ[k=1:n] a[k] x^k`	$\sum_{k=1}^{n} a_k x^k$
`C = A UNION B`	`C = A ∪ B`	$C = A \cup B$

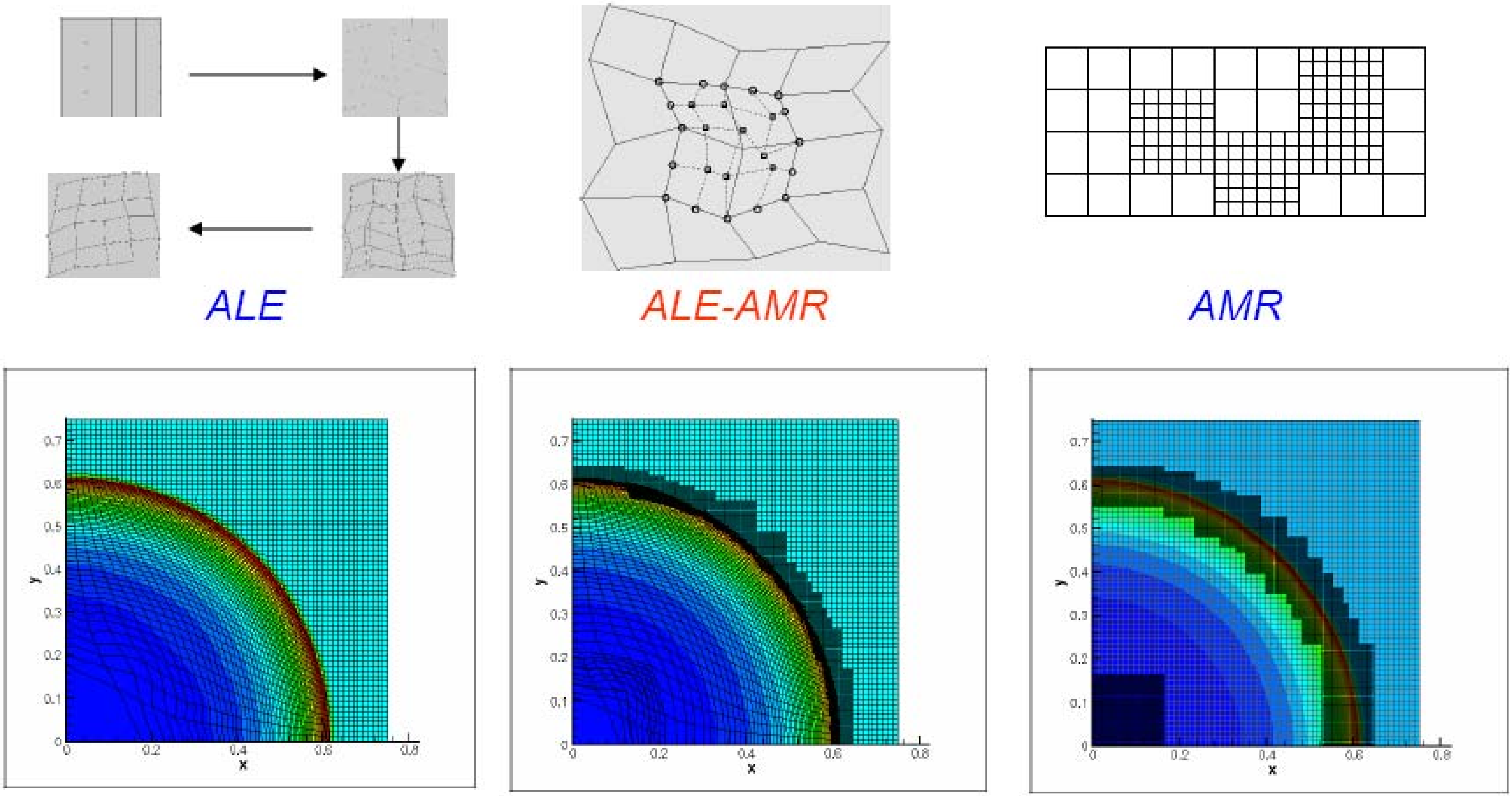
Key Ideas

- Use of global name space (Convenience; All)
- Locales are explicit entities (Essential for managing locality; all but Fortress)
- “Local” and “Global” data accesses are syntactically distinct (Essential for efficient compilation; all)
- Extensibility (Fortress)

Requirements for Efficient Use of Global Name Space

- Names of data and threads are independent of their location
- Arrays are distributed (all)
- Rich set of distributions; e.g. block-block, user-defined (Chapel, Fortress)
- Arrays can be redistributed (possible in Fortress via suitable library)
- Computations can be dynamically allocated and reallocated (?)

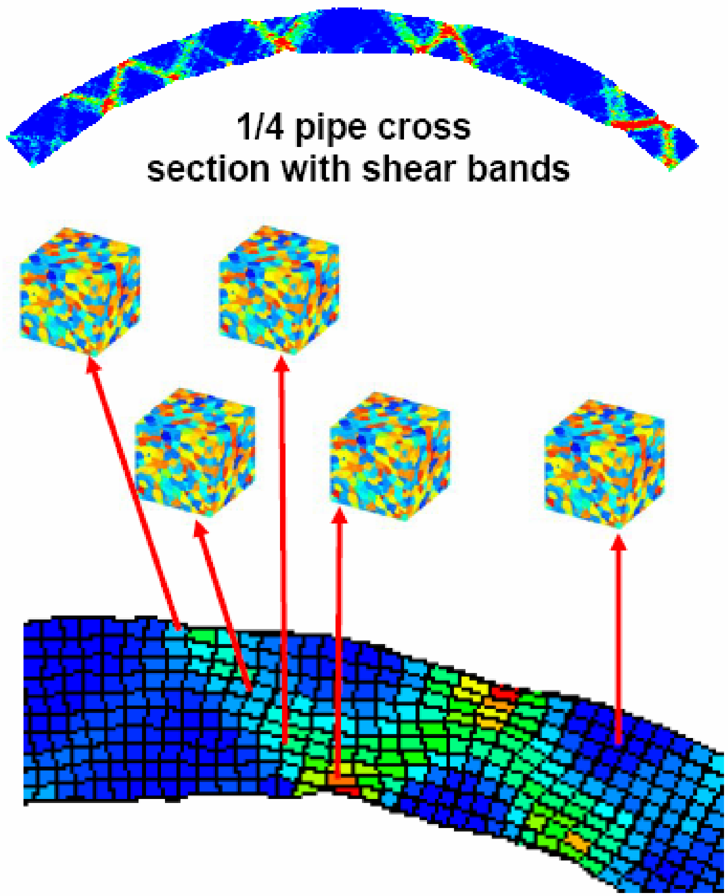
Why Dynamic Data Redistribution?

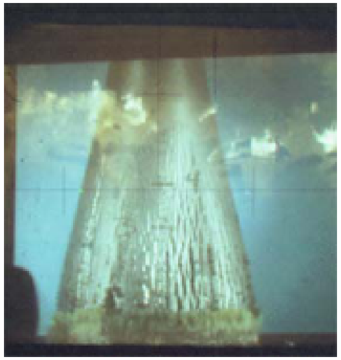


courtesy Steve Ashby

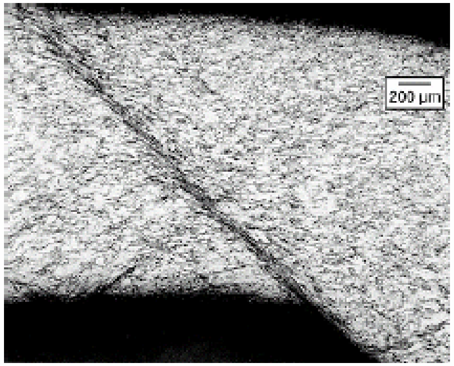
Why Dynamic Process Migration?

Expanding cylinder model with 50 grains at each FE integration point





Exploding cylinder



Shear bands in a Ta-10W tube

With *adaptive sampling*, fine scale models do not run everywhere, but only where interpolation from previous response functions is not sufficiently accurate

courtesy Steve Ashby

Locale Virtualization

- Static model: Parallel programs written for constant number of processors, running at same speed and with same storage
  - Most new languages use fixed number of locales
- Programs written for static model do not compose
  - Composition requires either separate set of processors or transfer of control on all processors
- Need virtualized locales (Fortress? X10?)
- Multiple gains accruing from virtualization

  load balancing, communication/computation overlap, communication aggregation, improved cache performance...

New Languages -- Diagnostic

- Each of the proposed languages would be an advance over MPI, if properly implemented
- All of the proposed languages still miss key features
- None address directly node performance bottlenecks and scaling problems
- X10, Chapel and especially Fortress require sophisticated compiler technology

Non Technical Obstacles

- It takes money to make a good compiler; there is no market for HPC unique optimizations
- It takes time to make a good compiler; there is no funding mechanism for a sustained 5 years development effort
- It takes people to make a good compiler; there is no independent compiler company
  - Should hw vendors develop the HPC ADE?

Minimal Solution Beyond MPI

- Compiled communication, to avoid software overhead
  - Possibly, inlining and optimization of key MPI calls
  - Alternatively, simple language extensions for access and update of remote variables (v; v@proc)
    - Not that different from CAF!
- Process virtualization, to support composability, load balancing, communication/computation overlap, communication aggregation, improved cache performance...

A Good ADE is More than Language

- Porting tools
- Good support for performance tuning
  - Tools for refactoring
  - Notation for capturing tuning decisions
- Good observability
  - integrated performance stream mining

Summary

- HPC is hampered by lack of good software support
- Language is only part of the problem
- Most obstacles are not technological
- Key issues for petascale computing are not yet being addressed
  - HPCS is driving high quality parallel computing language research, but this research pays little attention to petascale