Changing How Programmers Think about Parallel Programming

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Outline

- Why Parallel Programming?
- What are some ways to think about parallel programming?
- Thinking about parallelism: Bulk Synchronous Programming
- Why is this bad?
- How should we think about parallel programming
- Separate the Programming Model from the Execution Model
- Rethinking Parallel Computing
- How does this change the way you should look at parallel programming?
- Example

Why Parallel Programming?

- Because you need more computing resources that you can get with one computer
  - The focus is on *performance*
  - Traditionally compute, but may be memory, bandwidth, resilience/reliability, etc.
- High Performance Computing
  - Is just that – ways to get exceptional performance from computers – includes both parallel and sequential computing

What are some ways to think about parallel programming?

- At least two easy ways:
  - Coarse grained - Divide the problem into big tasks, run many at the same time, coordinate when necessary. Sometimes called "Task Parallelism"
  - Fine grained - For each "operation", divide across functional units such as floating point units. Sometimes called "Data Parallelism"

Example – Coarse Grained

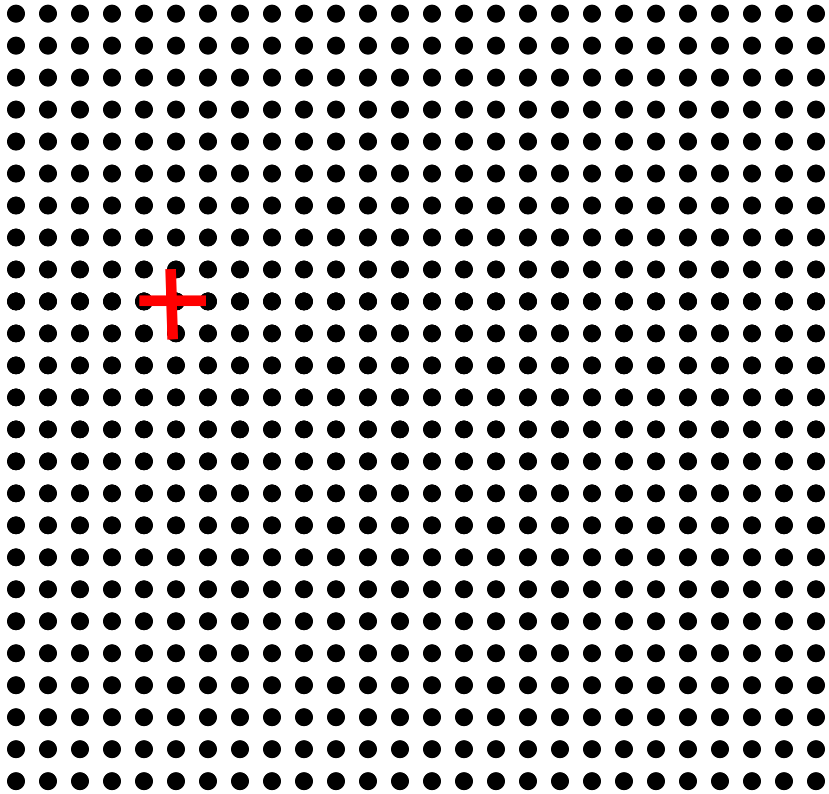
- Set students on different problems in a related research area
  - Or mail lots of letters – give several people the lists, have them do everything
  - Common tools include threads, fork, TBB

Example – Fine Grained

- Send out lists of letters
  - break into steps, make everyone write letter text, then stuff envelope, then write address, then apply stamp. Then collect and mail.
  - Common tools include OpenMP, autoparallelization or vectorization
- Both coarse and fine grained approaches are relatively easy to think about

Example: Computation on a Mesh

- Each circle is a mesh point
- Difference equation evaluated at each point involves the four neighbors
- The red "plus" is called the method's stencil
- Good numerical algorithms form a matrix equation Au=f; solving this requires computing Bv, where B is a matrix derived from A. These evaluations involve computations with the neighbors on the mesh.



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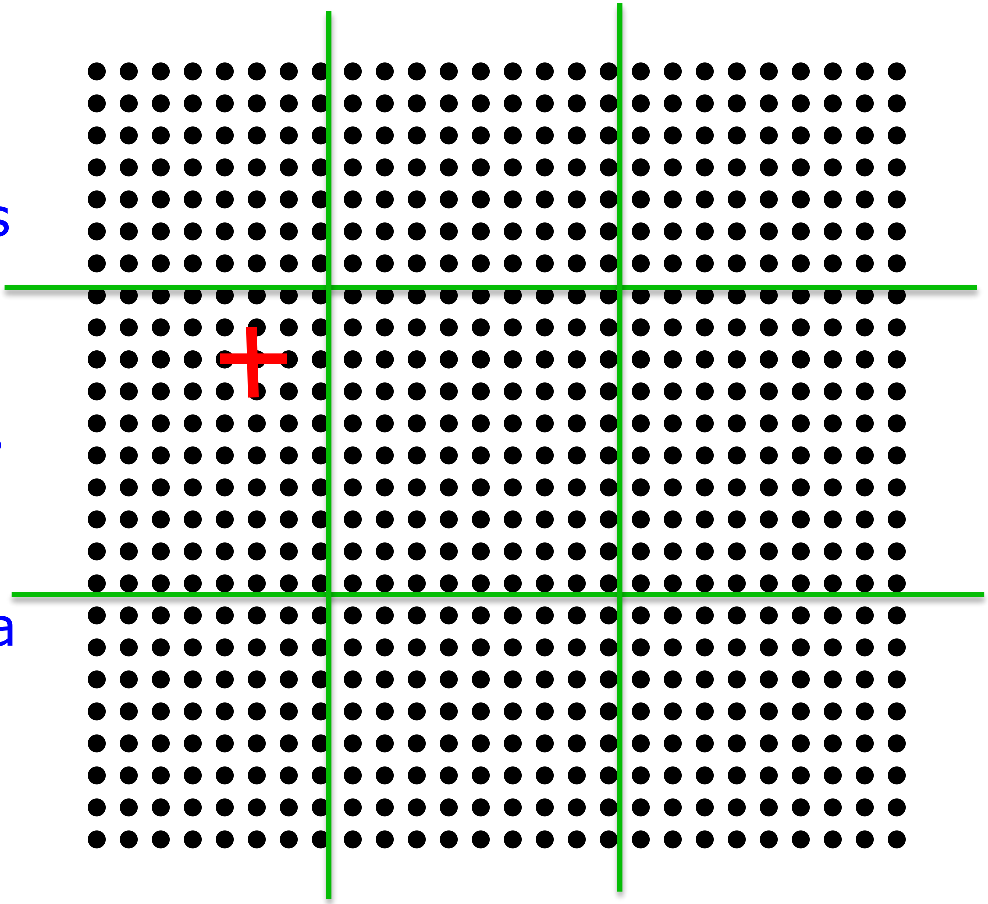
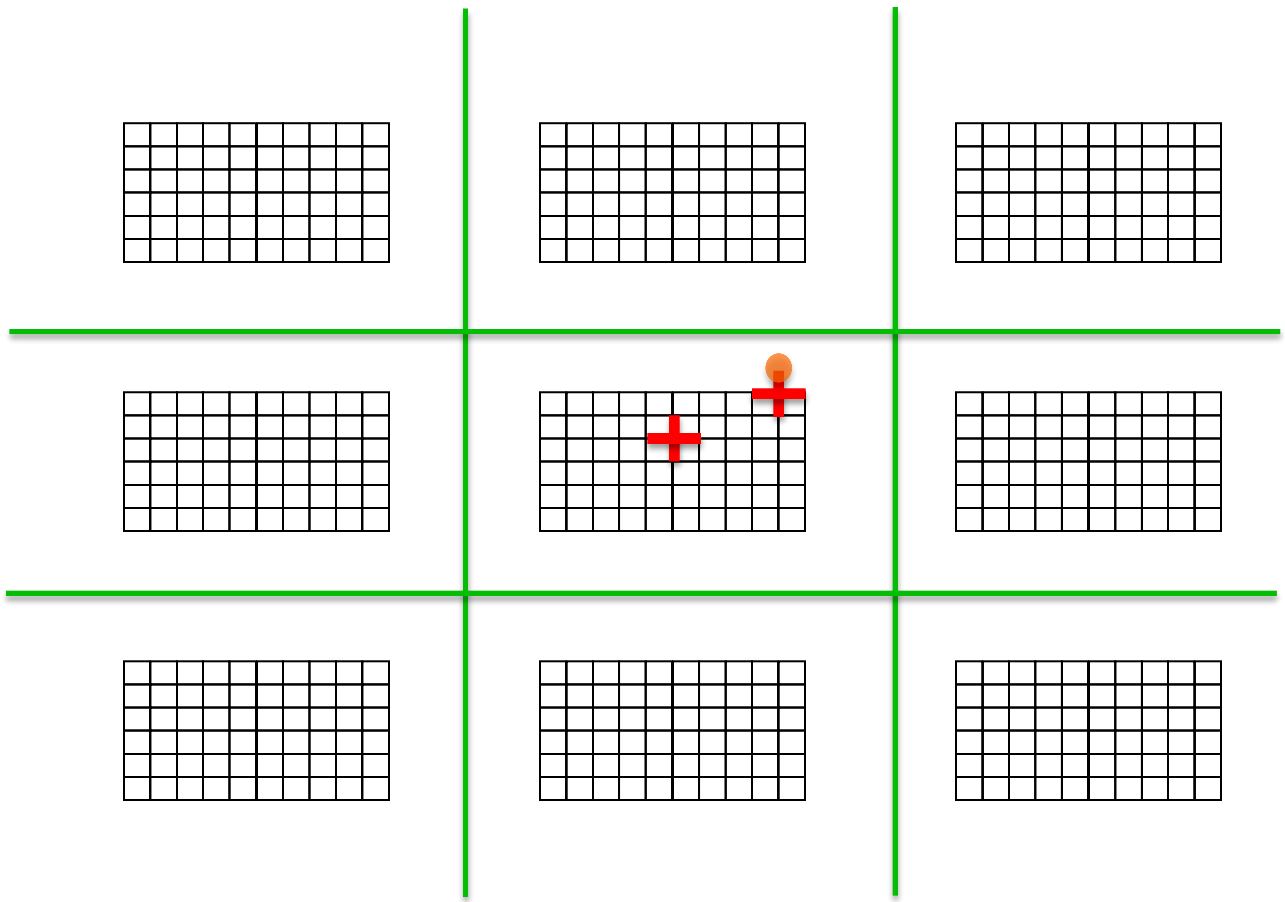
- Decompose mesh into equal sized (work) pieces



Necessary Data Transfers



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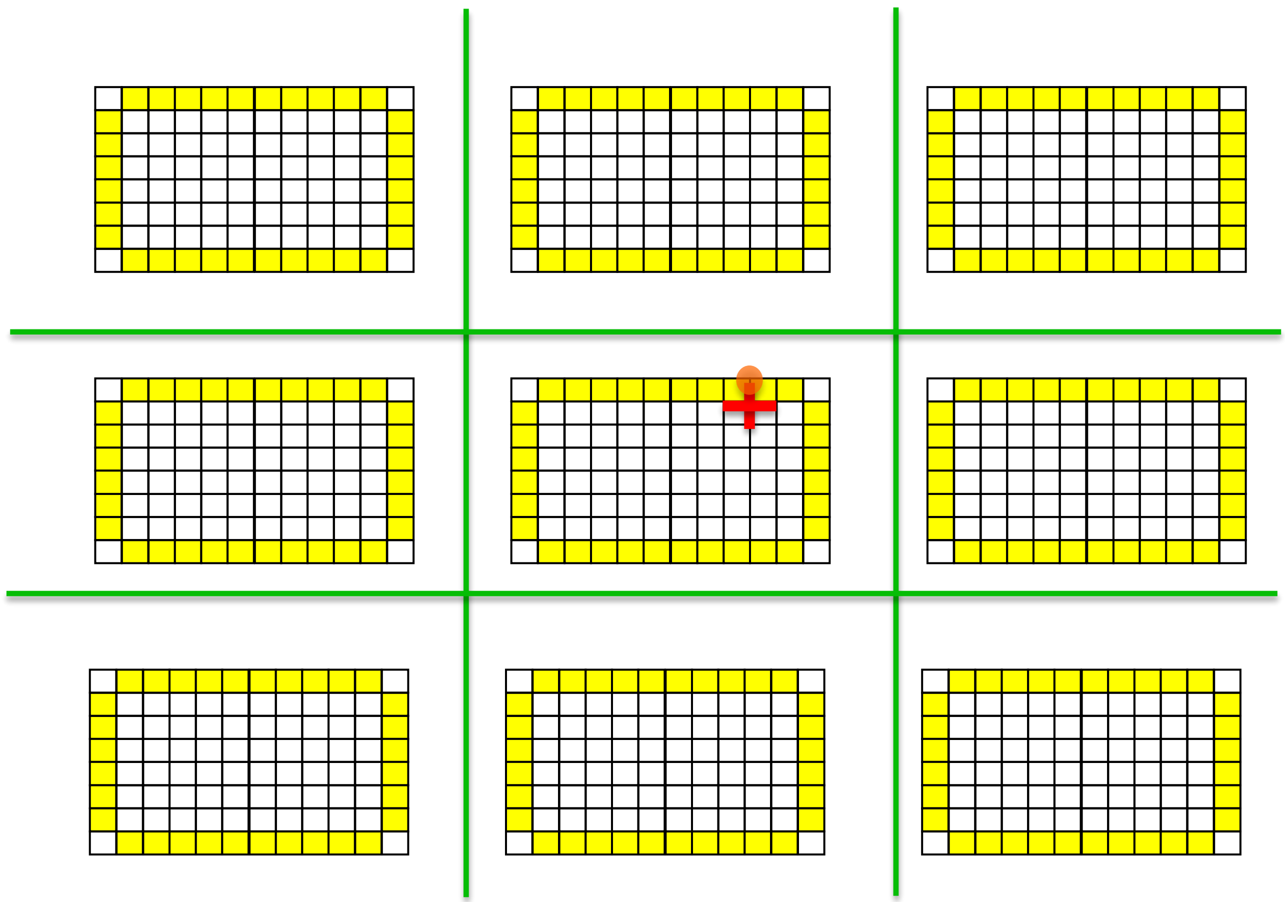
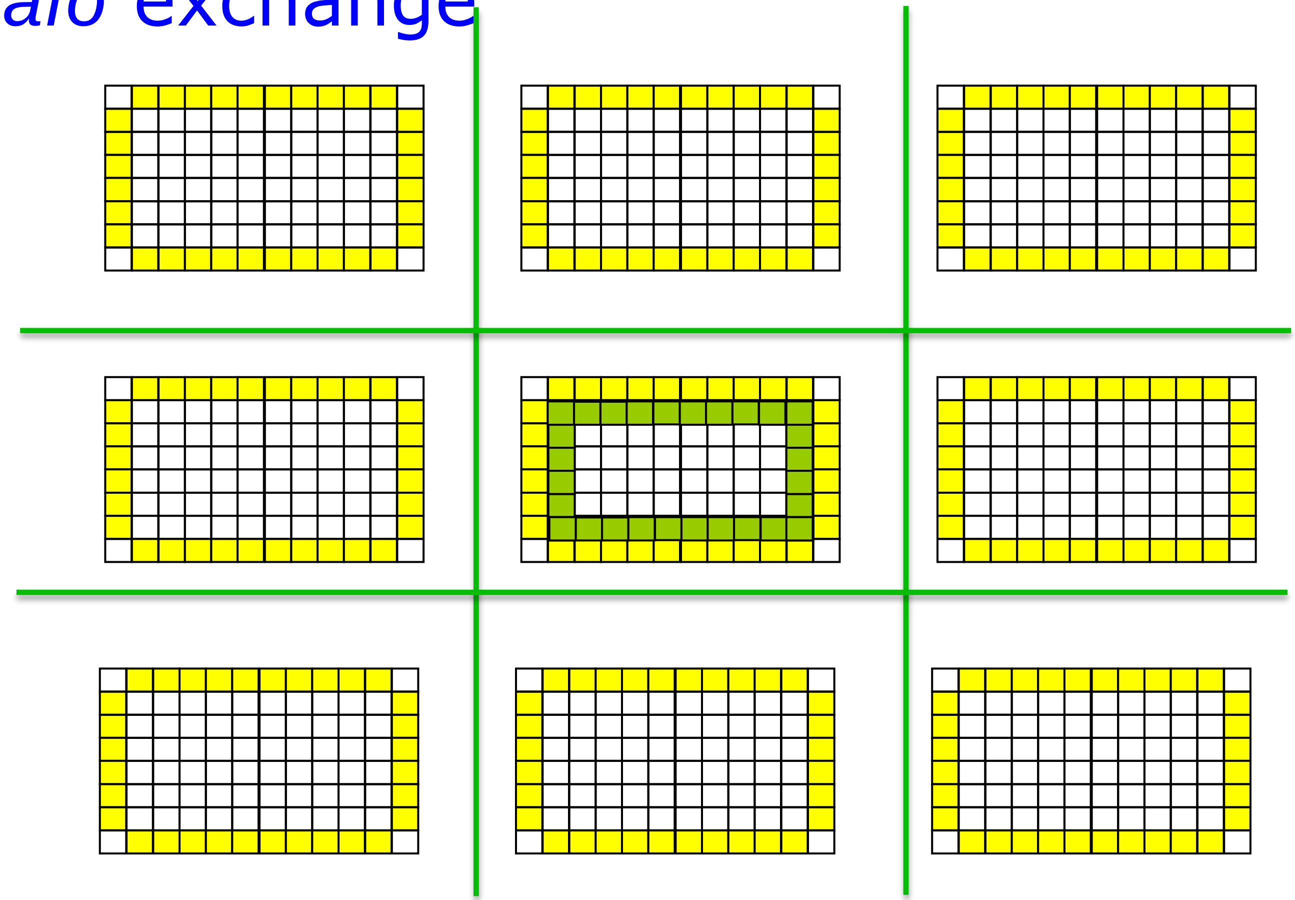


Necessary Data Transfers

- Provide access to remote data through a *halo* exchange



PseudoCode

- Iterate until done:
  - Exchange “Halo” data
    - MPI_Isend/MPI_Irecv/MPI_Waitall or MPI_Alltoallv or MPI_Neighbor_alltoall or MPI_Put/MPI_Win_fence or …
  - Perform stencil computation on local memory
    - Can use SMP/thread/vector parallelism for stencil computation – E.g., OpenMP loop parallelism

Thinking about Parallelism

- Parallelism is *hard*
  - Must achieve both correctness and performance
  - Note for parallelism, performance *is* part of correctness.
- Correctness requires understanding how the different parts of a parallel program interact
  - People are bad at this
  - This is why we have multiple layers of management in organizations

Thinking about Parallelism: Bulk Synchronous Programming

- In HPC, refers to a *style* of programming where the computation alternates between communication and computation phases
- Example from the PDE simulation
  - Iterate until done:
    - Exchange data with neighbors (see mesh)
    - Apply computational stencil
    - Check for convergence/compute vector product

Communication

Local computation

Synchronizing communication

Thinking about Parallelism: Bulk Synchronous Programming

- Widely used in computational science and technical computing
  - Communication phases in PDE simulation (halo exchanges)
  - I/O, often after a computational step, such as a time step in a simulation
  - Checkpoints used for resilience to failures in the parallel computer

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Bulk Synchronous Parallelism

- What is BSP and why is BSP important?
  - Provides a way to think about performance and correctness of the parallel program
    - Performance modeled by computation step and communication steps separately
    - Correctness also by considering computation and communication separately
  - Classic approach to solving hard problems – break down into smaller, easier ones.
- BSP formally described in "A Bridging Model for Parallel Computation," CACM 33#8, Aug 1990, by Leslie Valiant
  - Use in HPC is both more and less than Valiant's BSP

Why is this bad?

- Not really bad, but has limitations
  - Implicit assumption: work can be evenly partitioned, or at least evenly enough
    - But how easy is it to accurately predict performance of some code or even the difference in performance in code running on different data?
    - Try it yourself – What is the performance of *your* implementation of matrix-matrix multiply for a dense matrix (or your favorite example)?
    - Don't forget to apply this to every part of the computer – even if multicore, heterogeneous, such as mixed CPU/GPU systems
    - There are many other sources of performance irregularity – its hard to precisely predict performance

Why is this bad?

- Cost of "Synchronous"
  - Background: Systems are getting very large
    - Top systems have tens of thousands of nodes and order 1 million cores:
      - Tianhe-2 (China) 16,000 nodes
      - Blue Waters (Illinois) 25,000 nodes
      - Sequoia (LLNL) 98,304 nodes, >1M cores
  - Just getting all of these nodes to agree takes time
    - O(10usecs) or about 20,000 cycles of time)

Barriers and Synchronizing Communications

- Barrier:
  - Every thread (process) must enter before any can exit
- Many implementations, both in hardware and software
  - Where communication is pairwise, Barrier can be implemented in O(log p) time. Note $\log_2(10^6) \approx 20$
    - But each step is communication, which takes 1us or more
- Barriers rarely required in applications (see "functionally irrelevant barriers")

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Barriers and Synchronizing Communications

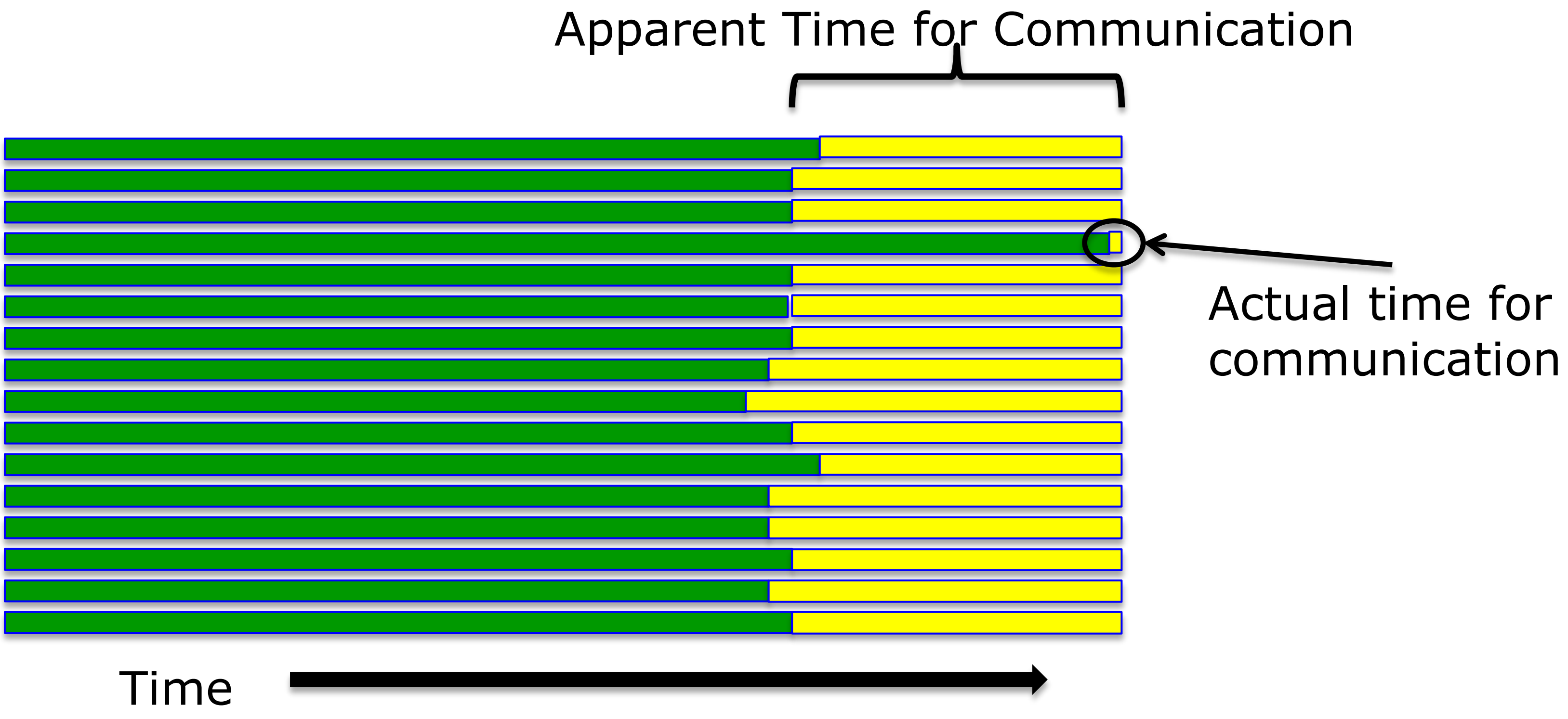
- A communication operation that has the property that all must enter before any exits is called a "synchronizing" communication
  - ♦ Barrier is the simplest synchronizing communication
  - ♦ Summing up a value contributed from all processes and providing the result to all is another example
    - Occurs in vector or dot products important in many HPC computations

Synchronizing Communication

- Other communication patterns are more weakly synchronizing
  - Recall the halo exchange example
  - While not synchronizing across all processes, still creates dependencies
    - Processes can’t proceed until their neighbors communicate
    - Some *programming implementations* will synchronize more strongly than required by the data dependencies in the algorithm

So What Does Go Wrong?

- What if one core (out of a million) is delayed?



- Everyone has to wait at the next synchronizing communication

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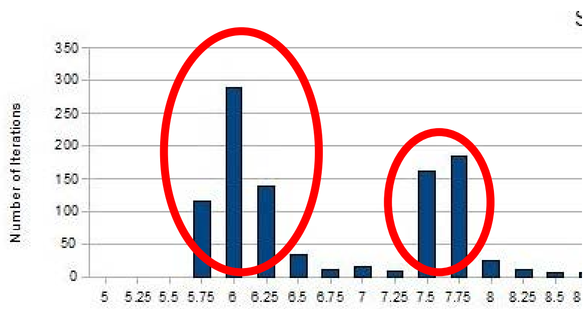
And It Can Get Worse

- What if while waiting, another core is delayed?
  - "Characterizing the Influence of System Noise on Large-Scale Applications by Simulation," Torsten Hoefler, Timo Schneider, Andrew Lumsdaine
    - Best Paper, SC10
  - Becomes more likely as scale increases – the probability that no core is delayed is $(1-f)^p$, where f is the probability that a core is delayed, and p is the number of cores
    - $\approx 1 - pf + \ldots$
- The delays can cascade

Many Sources of Delays

- Dynamic frequency scaling (power/temperature)
- Adaptive routing (network contention/resilience)
- Deep memory hierarchies (performance, power, cost)
- Dynamic assignment of work to different cores, processing elements, chips (CPU, GPU, …)
- Runtime services (respond to events both external (network) and internal (gradual underflow)
- OS services (including I/O, heartbeat, support of runtime)
- etc.



Summary so Far

- BSP (in its general form) provides an effective way to reason about parallel programs in HPC
  - Addresses both performance and correctness
    - Formal models of performance in wide use, from Hockney's original T_c=a+rn to LogP any beyond
    - Increasing number of tools for evaluating correctness of communication patterns
- But increasingly poor fit to real systems, especially (but not only) at extreme scale

How should we think about parallel programming?

- Need a more formal way to think about programming
  - Must be based on the realities of real systems
  - Not the system that we wish we could build (see PRAM)
- Not talking about a *programming model*
  - Rather, first need to think about what an extreme scale parallel system can *do*
  - System – the hardware and the software together

Separate the Programming Model from the Execution Model

- What is an execution model?
  - It’s how you think about how you can use a parallel computer to solve a problem
- Why talk about this?
  - The execution model can influence what solutions you consider (see the *Whorfian hypothesis* in linguistics)
  - After decades where many computer scientists only worked with one execution model, we are now seeing new models and their impact on programming and algorithms

Examples of Execution Models

- Von Neumann machine:
  - Program counter
  - Arithmetic Logic Unit
  - Addressable Memory
- Classic Vector machine:
  - Add "vectors" – apply the same operation to a group of data with a single instruction
    - Arbitrary length (CDC Star 100), 64 words (Cray), 2 words (SSE)
- GPUs with collections of threads (Warps)

Programming Models and Systems

- In past, often a tight connection between the execution model and the programming approach
  - Fortran: FORmula TRANslation to von Neumann machine
  - C: e.g., "register", ++ operator match PDP-11 capabilities, needs
- Over time, execution models and reality changed but programming models rarely reflected those changes
  - Rely on compiler to "hide" those changes from the user – e.g., auto-vectorization for SSE(n)
- Consequence: Mismatch between users' expectation and system abilities.
  - Can't fully exploit system because user's mental model of execution does not match real hardware
  - Decades of compiler research have shown this problem is extremely hard – can't expect system to do everything for you.

Programming Models and Systems

- Programming Model: an abstraction of a way to write a program
  - Many levels
    - Procedural or imperative?
    - Single address space with threads?
    - Vectors as basic units of programming?
  - Programming model often expressed with pseudo code
- Programming System: (My terminology)
  - An API that implements parts or all of one or more programming models, enabling the precise specification of a program

Why the Distinction?

- In parallel computing,
  - Message passing is a programming model
    - Abstraction: A program consists of processes that communication by sending messages. See "Communicating Sequential Processes", CACM 21#8, 1978, by C.A.R. Hoare.
  - The Message Passing Interface (MPI) is a programming system
    - Implements message passing and other parallel programming models, including:
    - Bulk Synchronous Programming
    - One-sided communication
    - Shared-memory (between processes)

  - CUDA/OpenACC/OpenCL are systems implementing a "GPU Programming Model"
    - Execution model involves teams, threads, synchronization primitives, different types of memory and operations

The Devil Is in the Details

- There is no unique execution model
  - What level of detail do you need to design and implement your program?
    - Don’t forget – you decided to use parallelism because you could not get the performance you need without it
- Getting what you need already?
  - Great! It ain’t broke
- But if you need more performance of any type (scalability, total time to solution, user productivity)
  - Rethink your model of computation and the programming models and systems that you use

Rethinking Parallel Computing

- Changing the execution model
  - No assumption of performance regularity – but not unpredictable, just imprecise
    - Predictable within limits and most of the time
  - Any synchronization cost amplifies irregularity – don't include synchronizing communication as a desirable operation
  - Memory operations are always costly, so moving operation to data may be more efficient
    - Some hardware designs provide direct support for this, not just software emulation
  - Important to represent key hardware operations, which go beyond simple single ALU
    - Remote update (RDMA)
    - Remote operation (compare and swap)
    - Execute short code sequence (Active Messages, parcels)

How does this change the way you should look at parallel programming?

- More dynamic. *Plan* for performance irregularity
  - But still exploit as much regularity as possible to minimize the overhead)
- Recognize communication takes time, which is not precisely predictable
  - Communication between cache and memory or between two nodes in a parallel system
- Think about the *execution model*
  - *Your* abstraction of how a parallel machine works
  - Include the hardware-supported features that you need for performance
- Finally, use a programming system that lets you express the elements you need from the execution model.

Example: The Mesh Computation

- Rethinking: Performance not perfectly predictable, so must not assume that a perfect data distribution gives a perfect work distribution
    - One solution: "over decompose" mesh into more pieces that there are processes or threads; use a combination of a priori and dynamic scheduling to adapt
- Rethinking: Communication dependencies introduce delays
    - Many solutions: Use one-sided communication; use non-blocking communication; use multi-step algorithms; use over decomposition to give greater flexibility to comm schedule, …

Take Away

- Be aware of the capabilities of a parallel system
  - Not just what a particular programming *model* provides
- Think about the realities of execution on your parallel computer
  - Use as simple an abstraction as possible *but no simpler*
- Find a programming *system* with which you can efficiently express your algorithm
  - Don't be confused by statements that a particular programming system only implements a single programming model or only works with a single execution model

Further Investigation

- Programming systems and tools that support a more dynamic form of computing:
  - Charm++ and Adaptive MPI
  - DAQUE, used in the MAGMA and PLASMA numerical libraries
  - Many thread-based tools, such as TBB; "guided" scheduling in OpenMP
  - Don't forget to explore the full capabilities of MPI-3

Further Investigation

- Research systems
  - EARTH and EARTH Threaded-C http://www.capsl.udel.edu/earth.shtml
  - XPRESS, HPX and ParalleX https://www.xstackwiki.com/index.php/XPRESS (and see other X-Stack projects)

Further Investigation

- Algorithms
  - Nonblocking reductions in Conjugate Gradient
  - Multistep methods (reduce, not eliminate synchronizing collectives)
  - Data-centric graph algorithms (move computation to data, rather than remote access of data)

Further Investigation

- Many more; the preceding is just a small sampling
- Search for "execution model parallel computing"
- Meet with others using parallel programming
  - We recommend SC13, November 17-22, in Denver!

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