The Coming Era of *Adaptive Control Systems* in HPC

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Just as I was preparing this

- I read an abstract of a talk yesterday:
  - “Supercomputing has had two "easy" decades”
    - where most of the increased performance of supercomputers came from the increase in uniprocessor performance
- I thought we were having fun these decades
  - But not because it was easy
- But then, I trust Marc Snir (who said this)..
  - And he did put those quotes
  - So, it means its going to get even harder
    - We all know why: sophisticated apps, complex machines
  - More fun, and more employment!

What *control systems* am I talking about?

- Runtime Systems?
- Java runtime:
  - JVM + Java class library
  - Implements JAVA API
- MPI runtime:
  - Implements MPI standard API
  - Mostly mechanisms
- I want to focus on runtimes that are “smart”
  - i.e. include strategies in addition to mechanisms
  - Many mechanisms to enable adaptive strategies

Why?

And what kind of adaptive runtime system I have in mind?

Let us take a detour

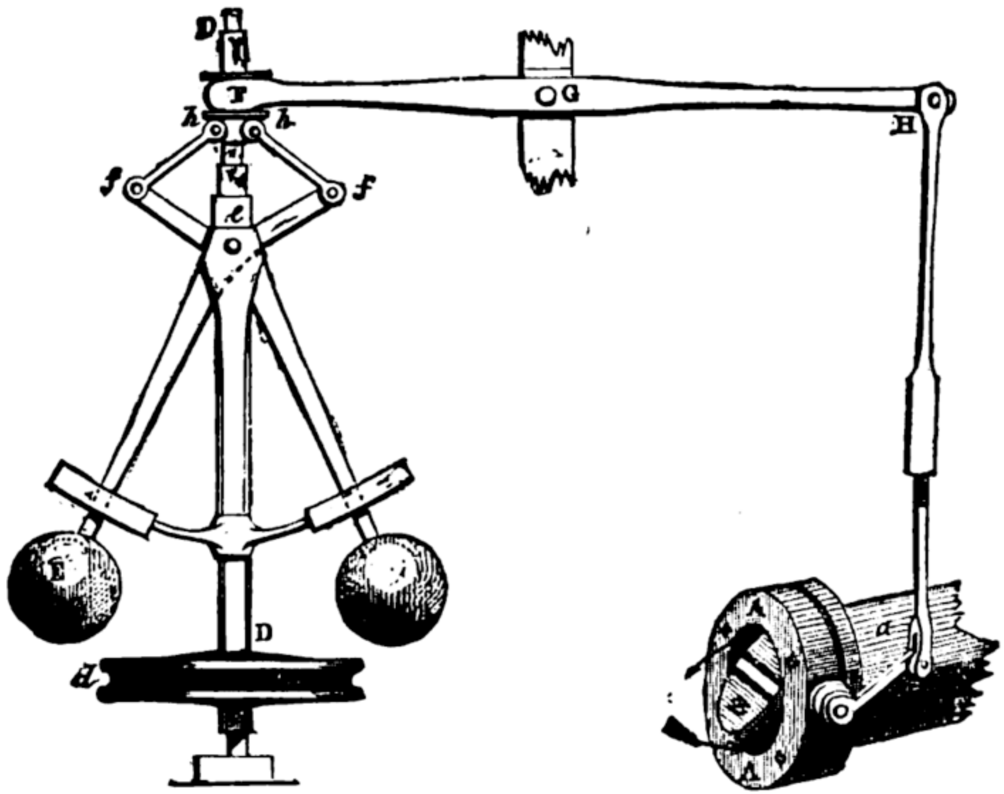


FIG. 4.—*Governor and Throttle-Valve.*

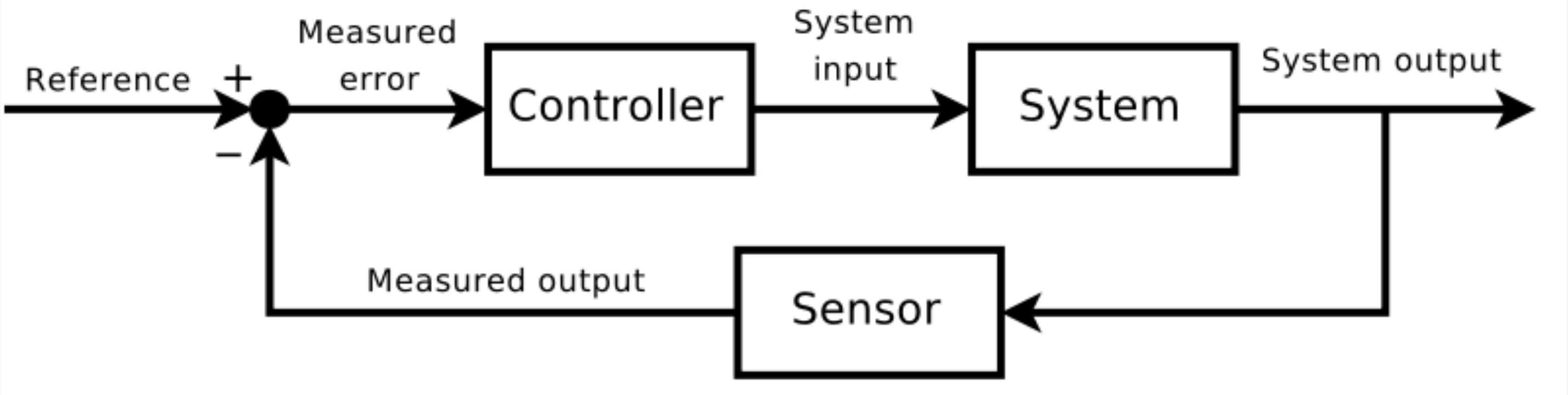
Source: Wikipedia

Governors

- Around 1788 AD, James Watt and Mathew Boulton solved a problem with their steam engine
  - They added a cruise control… well, RPM control
  - How to make the motor spin at the same constant speed
  - If it spins faster, the large masses move outwards
  - This moves a throttle valve so less steam is allowed in to push the prime mover

Feedback Control Systems Theory

- This was interesting:
  - You let the system "misbehave", and use that misbehavior to correct it..
  - Of course, there is a time-lag here
  - Later Maxwell wrote a paper about this, giving impetus to the area of "control theory"

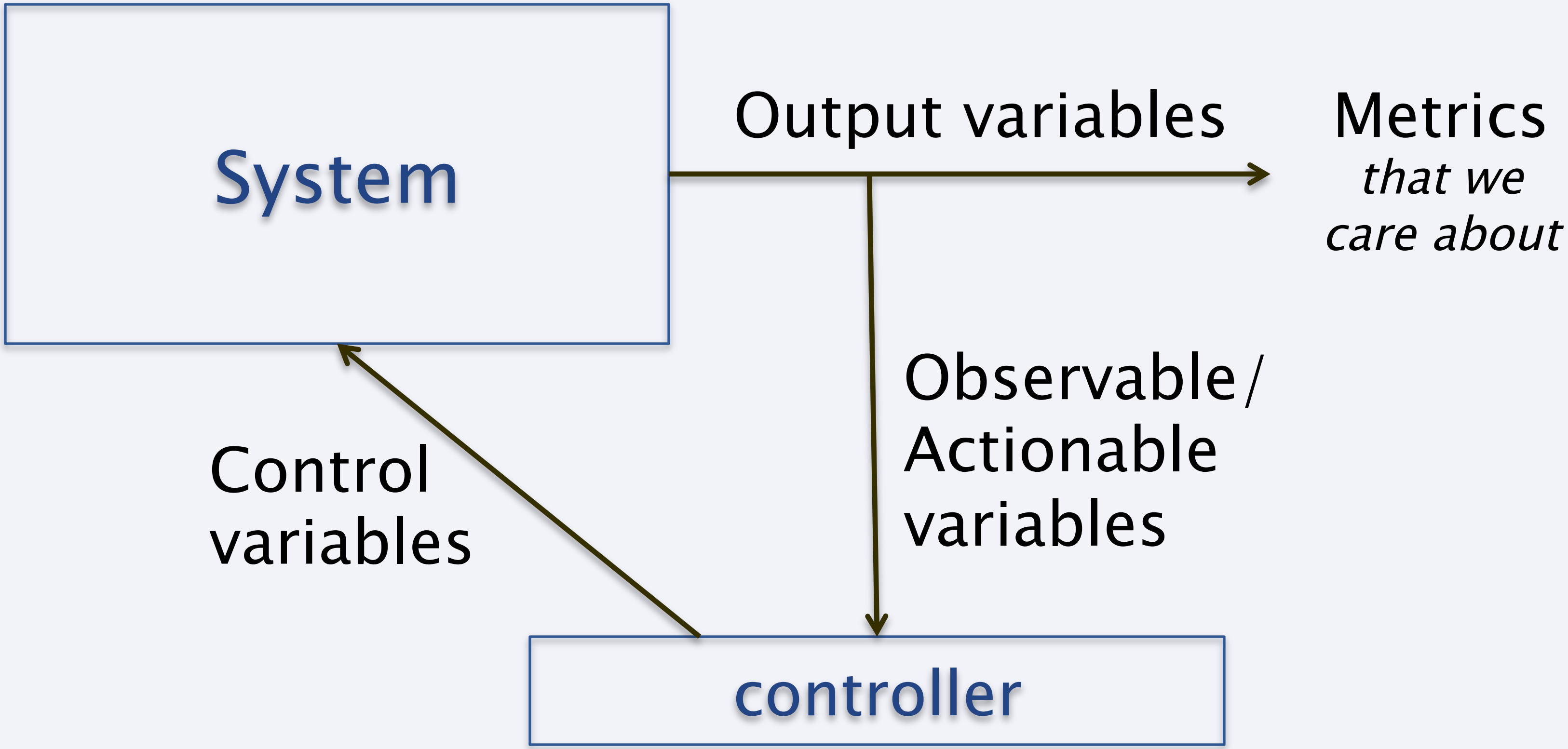


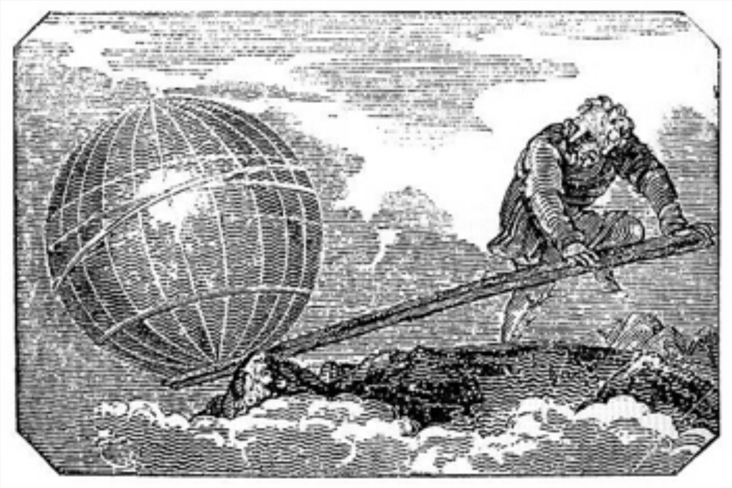
Source: Wikipedia

Control theory

- The control theory was concerned with stability, and related issues
  - Fixed delay makes for highly analyzable system with good math demonstration
- We will just take the basic diagram and two related notions:
  - Controllability
  - Observability

A modified system diagram





Source: Wikipedia

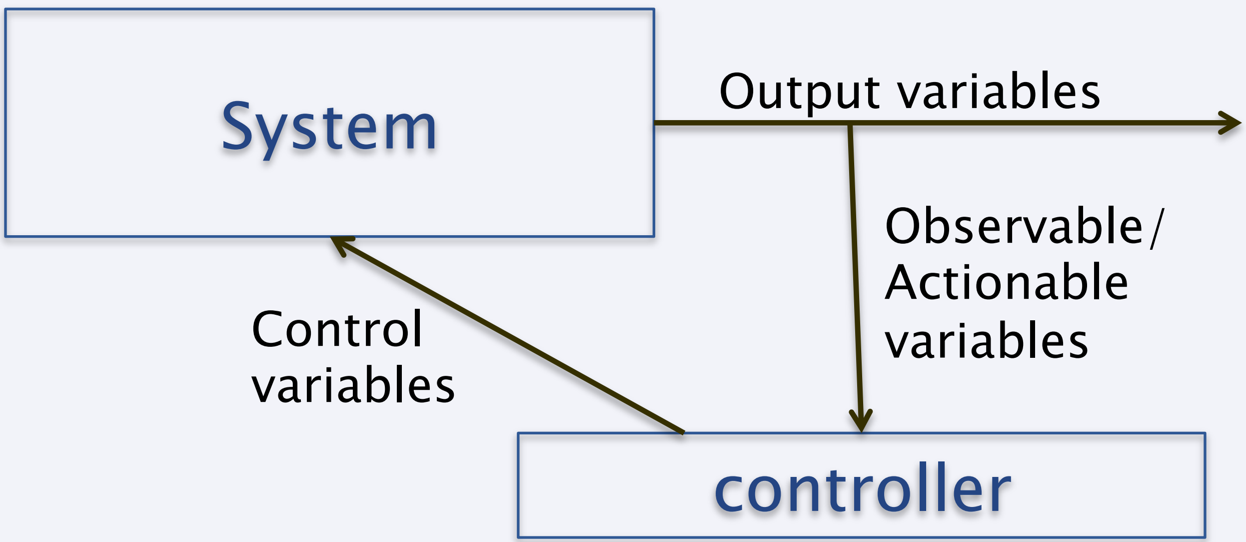
Archimedes is supposed to have said, of the lever:

Give me a place to stand on,
and I will move the Earth

Need to have the lever

- **Observability:**
  - If we can't observe it, can't act on it
- Controllability:
  - If no appropriate control variable is available, we can't control the system
    - (bending the definition a bit)
- So: <u>an effective control system needs to have a rich set of observable and controllable variables</u>

A modified system diagram



some of these are
Metrics
that we care about

These include one or more:

- <u>Objective functions</u> (minimize, maximize, optimize)
- <u>Constraints:</u> “must be less than”, ..

Feedback Control Systems in HPC?

- Let us consider two “systems”
  - And examine them for opportunities for feedback control
- A parallel “job”
  - A single application running in some partition
- A parallel machine
  - Running multiple jobs from a queue

A Single Job

- System output variables that we care about:
  - (Other than the job's science output)
  - Execution time, energy, power, memory usage, ..
  - First two are objective functions
  - Next two are (typically) constraints
  - We will talk about other variables as well, later
- What are the observables?
  - Maybe message sizes, rates? Communication graphs?
- What are the control variables?
  - Very few. Maybe MPI buffer size? Bigpages?

Control System for a single job?

- Hard to do, mainly because of the paucity of control variables
- This was a problem with "Autopilot", Dan Reed's otherwise exemplary research project
  - Sensors, actuators and controllers could be defined, but the underlying system did not present opportunities
- We need to "open up" the single job to expose more controllable knobs

Alternatives

- Each job has its own ARTS control system, for sure
- But should this be:
  - Specially written for that application?
  - A common code base?
  - A framework or DSL that includes an ARTS?
- This is an open question, I think..
  - But it must be capable of interacting with the machine-level control system
- My opinion:
  - Common RTS, but specializable for each application

The Whole Parallel Machine

- Consists of nodes, job scheduler, resource allocator, job queue, ..
- Output variables:
  - Throughput, energy bill, energy per unit of work, power, availability, reliability, ..
- Again, very little control
  - About the only decision we make is which job to run next, and which nodes to give to it..
  - Maybe a few more ideas now, in the context of energy:
    - How many nodes to leave idle
    - What power limit to assign to a job

The Big Question/s:

How to add more control variables?
How to add more observables?

And then, how to build a powerful adaptive control system?

It so happens ☺

- My group's research over the past 15-20 years can be thought of as a quest to add more observables and control variables
  - Programming models, languages ,libraries, including:
    - Charm++, AMPI, Charisma, MSA, Charj,
- Now, I'd like to consolidate the experience and knowledge gained, and express it in a new *abstract programming model*

XMAPP

- XMAPP is an abstract programming model:
  - That means it characterizes a set of prog. models
- For a programming model to belong to this set, it must support
  - X: Overdecomposition
    - (as in: 8X objects than cores)
  - M: Migratability
  - A: Asynchrony
    - and Adaptivity, as a consequence of all the above
- So, XMAPP stands for:
  - Overdecomposition-based Migratibility, Asynchrony and Adaptivity in Parallel Programming

Members of XMAPP-class

- The programming models in XMAPP, or exhibit some features of it
  - Charm++
  - Adaptive MPI
  - KAAPI
  - ProActive
  - FG-MPI (if it adds migration)
  - HPX (once it embraces migratability)
  - ParSEC
  - CnC
  - MSA (multi-phase Shared arrays)
  - Charisma
  - Charj
  - DRMS (old abstraction from IBM research..)
  - Chapel: may be a higher level model
  - X10: has asynchrony, but not migratable units
  - Tascel

Also, general work on adaptivity is relevant: Trilinos, Hank Hoffman/UIC, …

Over-decomposition

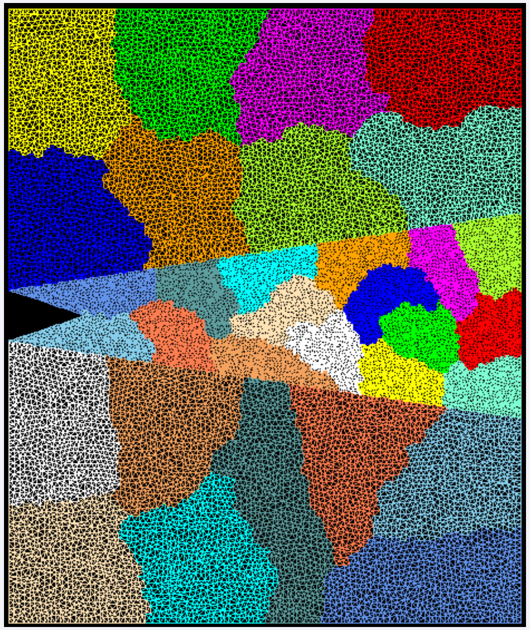
- Let the programmer decompose a computation into entities
  - Work units, data-units, composites
  - Into *coarse-grained* set of objects
  - Independent of number of processors
- Let the entities communicate with each other without reference to processors
  - So each entity is like a virtual processor by itself
- Let an intelligent runtime system assign these entities to processors
  - RTS can change this assignment during execution
- This empowers the control system
  - A large number of observables
  - Many control variables created

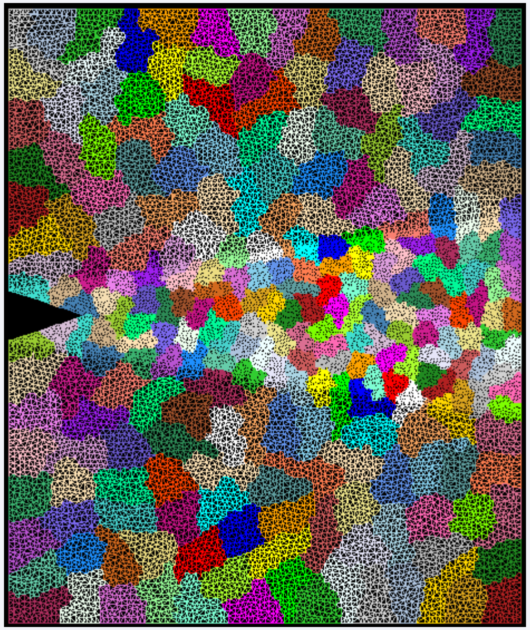
Grainsize

- It is important to understand what I mean by coarse-grained entities
  - You don't write sequential programs that some system will auto-decompose
  - You don't write programs when there is one object for each *float*
  - You consciously choose a grainsize, BUT choose it independent of the number of processors
    - Or parameterize it, so you can tune later

Crack Propagation

This is 2D, circa 2002…
but shows over-decomposition for unstructured meshes..





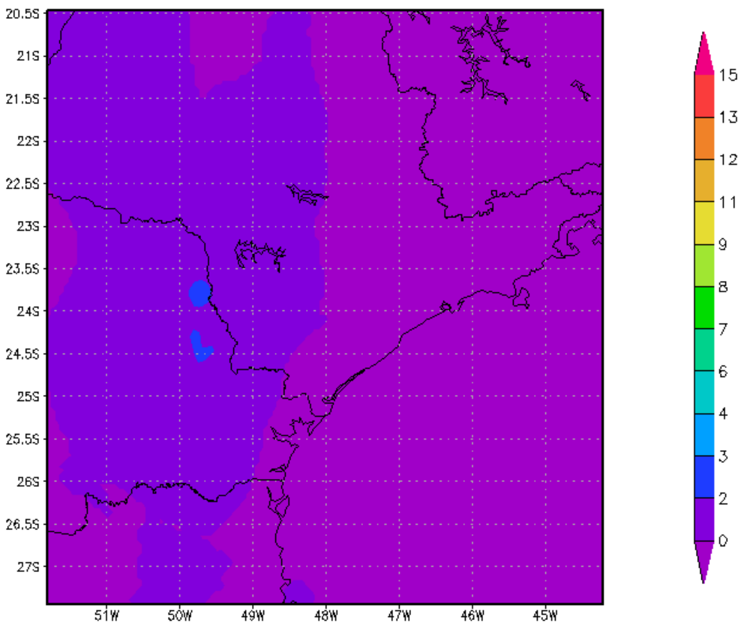
Decomposition into 16 chunks (left) and 128 chunks, 8 for each PE (right). The middle area contains cohesive elements. Both decompositions obtained using Metis. Pictures: S. Breitenfeld, and P. Geubelle

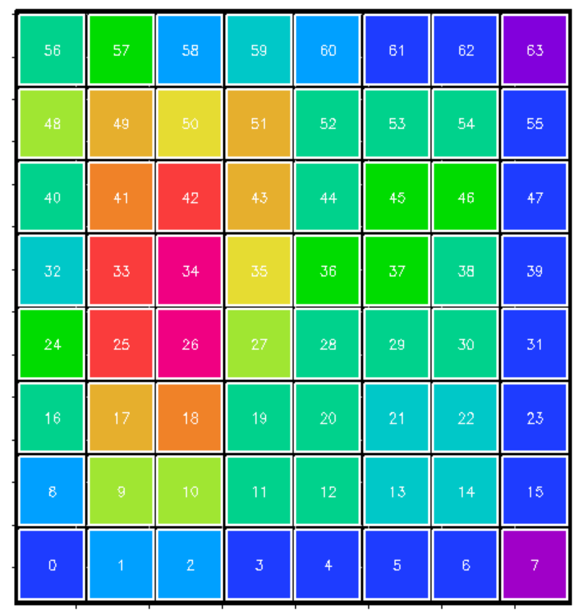
Grainsize example: NAMD

- High Performing examples: (objects are the work-data units in Charm++)
- On Blue Waters, 100M atom simulation,
  - 128K cores (4K nodes), 5,510,202 objects
- Edison, Apoa1(92K atoms)
  - 4K cores , 33124 objects
- Hopper, STMV, 1M atoms,
  - 15,360 cores, 430,612 objects

Grainsize: Weather Forecasting in BRAMS

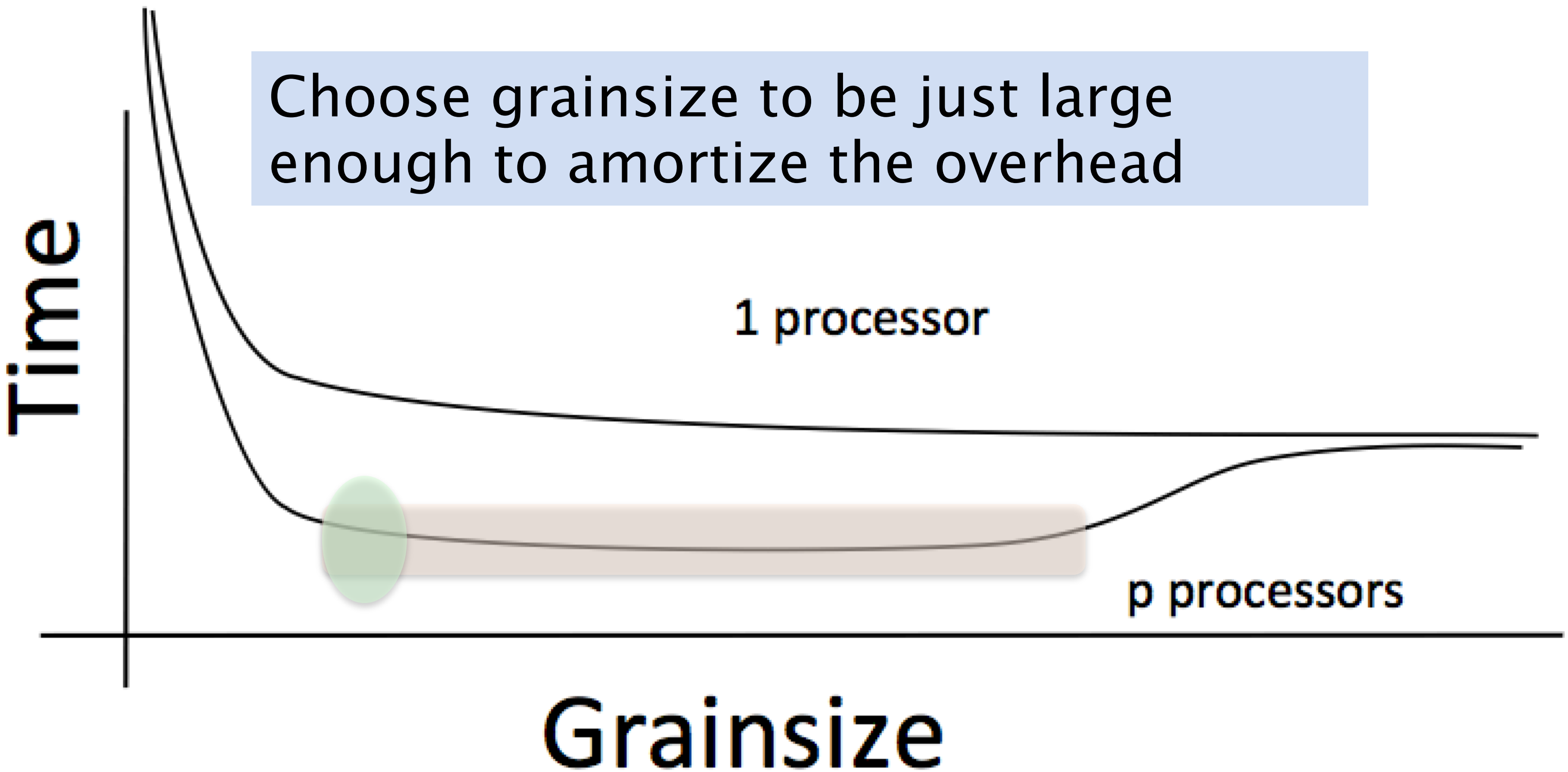
- Brams: Brazillian weather code (based on RAMS)
- AMPI version (Eduardo Rodrigues, with Mendes , J. Panetta, ..)



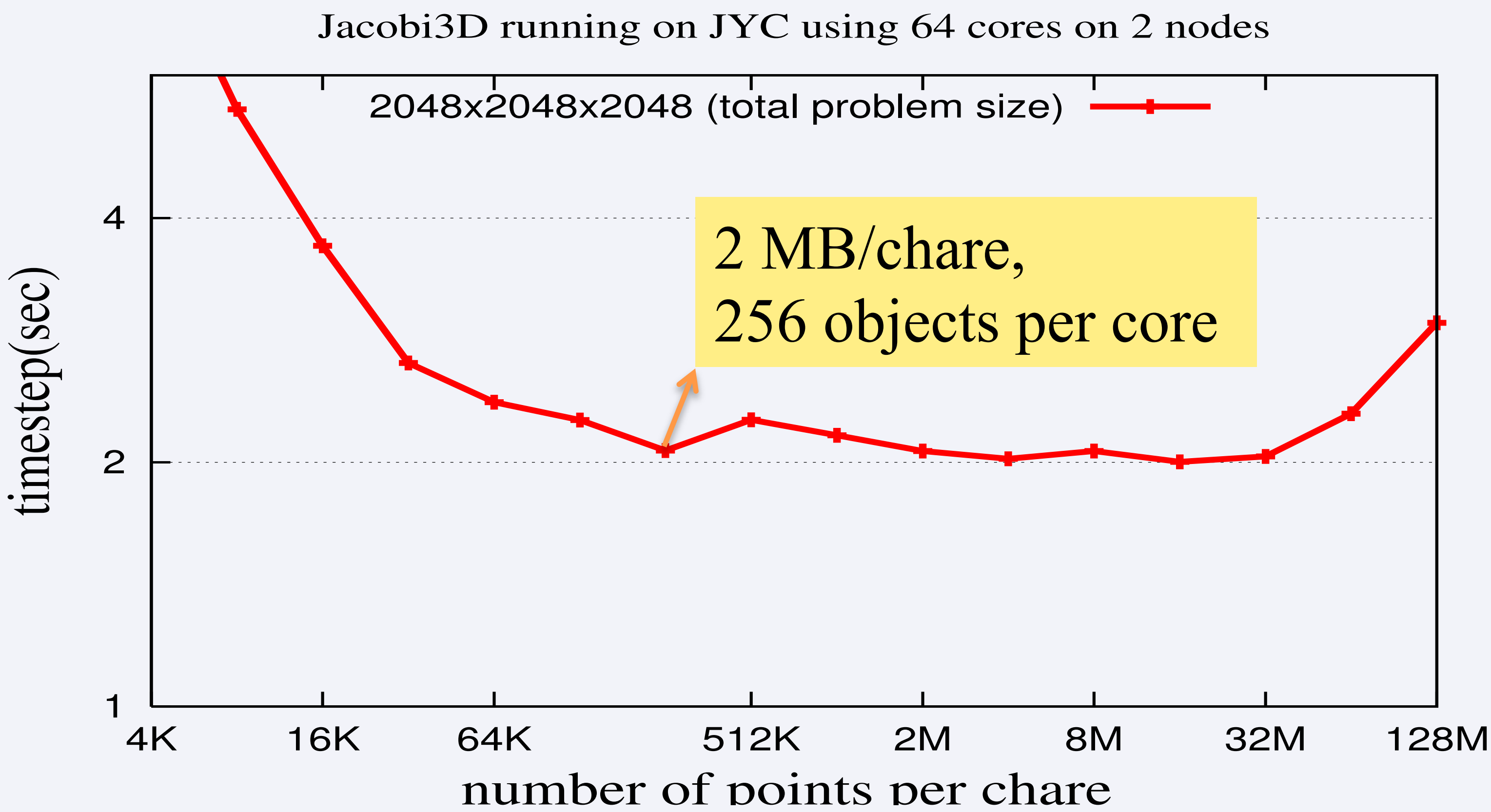


Instead of using 64 work units on 64 cores, used 1024 on 64

Working definition of grainsize :
amount of computation per remote interaction

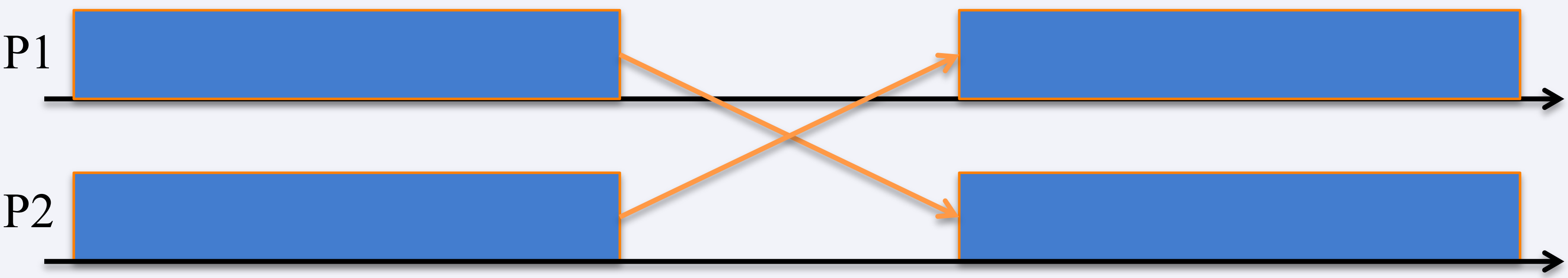


Grainsize in a common setting



Impact on communication

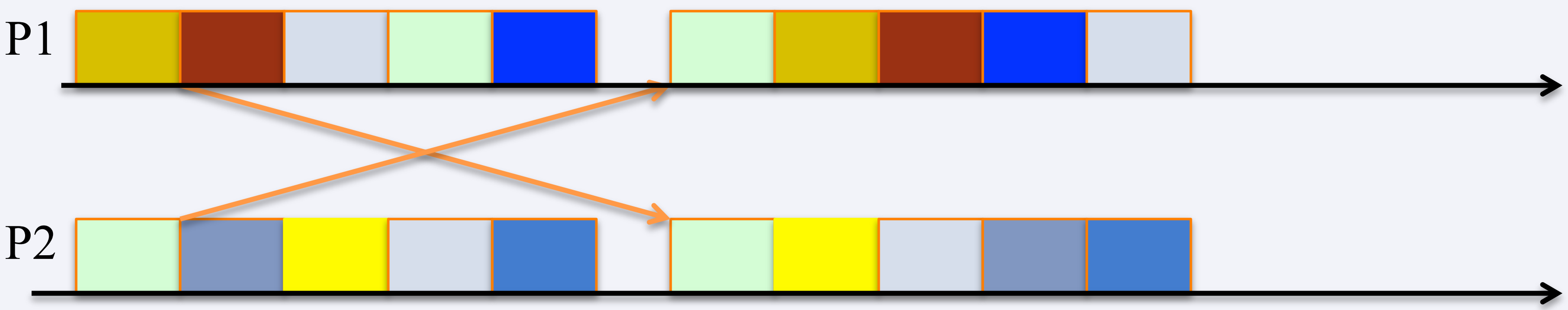
- Current use of communication network:
  - Compute-communicate cycles in typical MPI apps
  - So, the network is used for a fraction of time,
  - and is on the critical path
- So, current *communication networks are over-engineered for by necessity*



BSP based application

Impact on communication

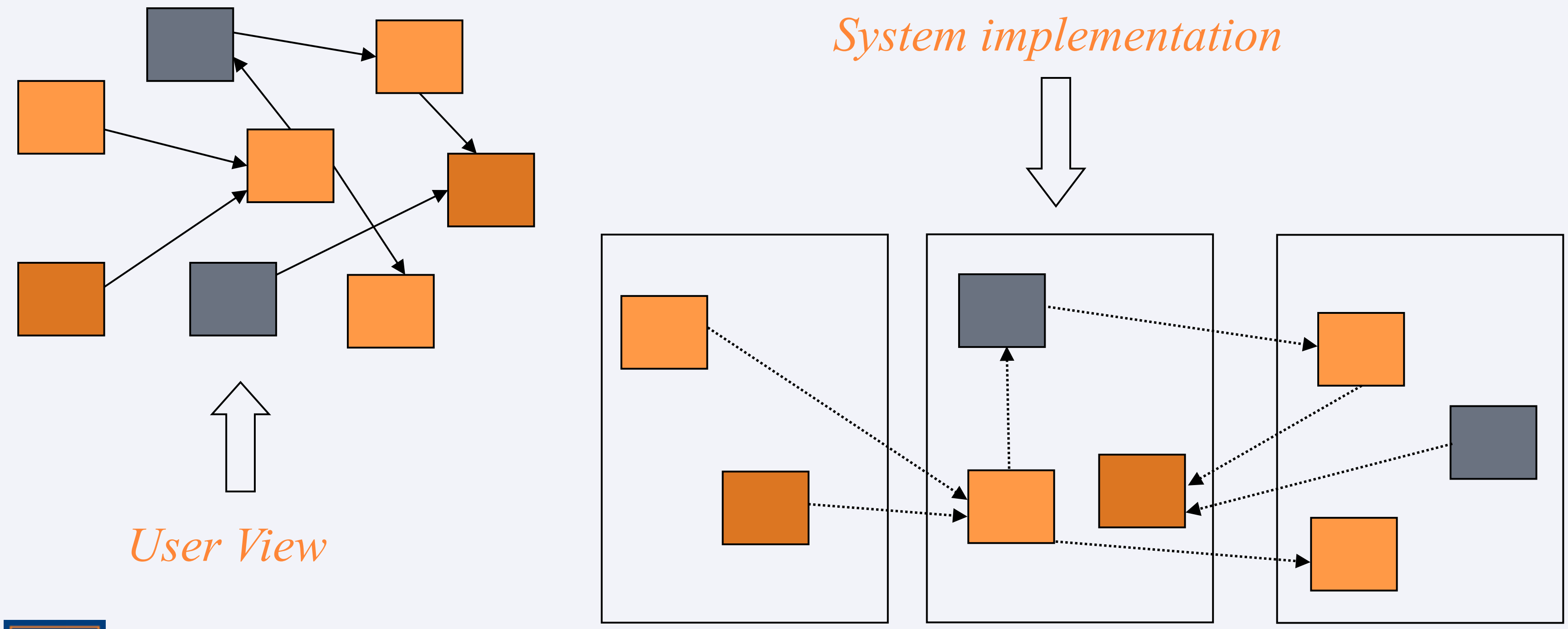
- With overdecomposition
  - Communication is spread over an iteration
  - Also, adaptive overlap of communication and computation

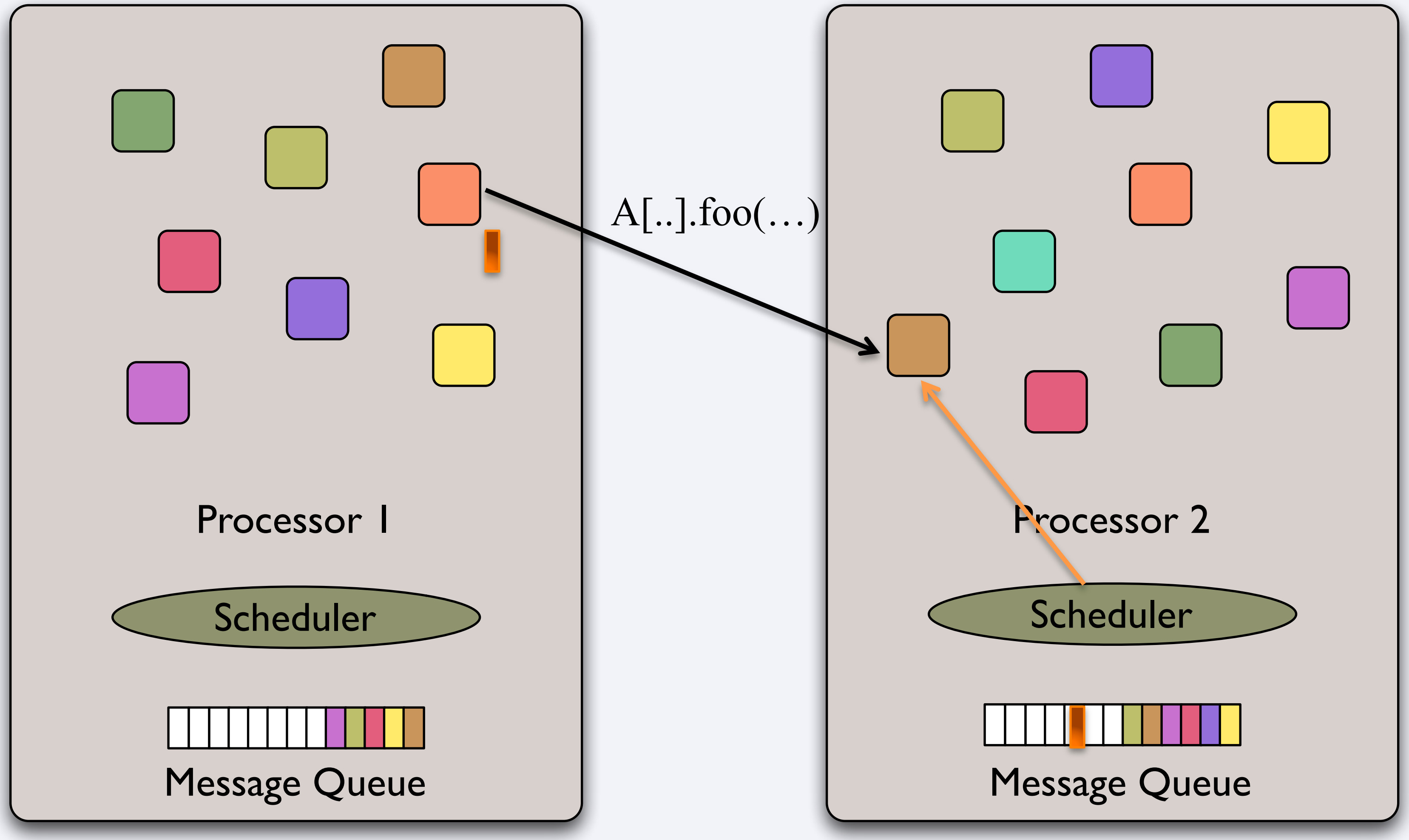


Overdecomposition enables overlap

Object-based over-decomposition: Charm++

- Multiple "indexed collections" of C++ objects
- Indices can be multi-dimensional and/or sparse
- Programmer expresses communication between objects
  - with no reference to processors





A[..].foo(…)
Processor 1
Scheduler
Message Queue
Processor 2
Scheduler
Message Queue

Note the control points created

- Scheduling (sequencing) of multiple method invocations waiting in scheduler's queue
- Observed variables: execution time, object communication graph (who talks to whom)
- Migration of objects
  - System can move them to different processors at will, because..
- This is already very rich…
  - What can we do with that??

Optimizations Enabled/Enhanced by These New Control Variables

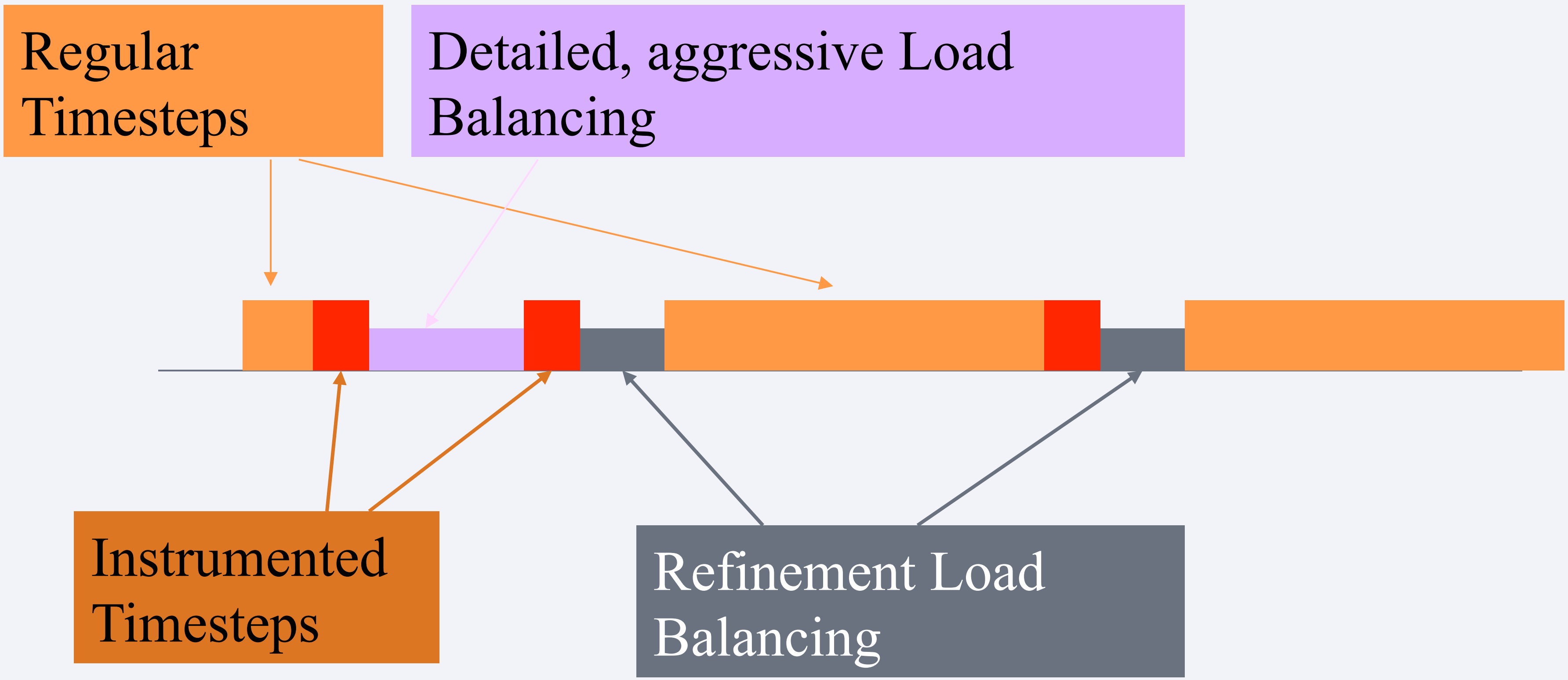
- Communication optimization
- Load balancing
- Meta-balancer
- Heterogeneous Load balancing
- Power/temperature/energy optimizations
- Resilience
- Shrink/Expand sets of nodes
- Application reconfiguration to add control points
- Adapting to memory capacity

Principle of Persistence

- Once the computation is expressed in terms of its natural (migratable) objects
- *Computational loads and communication patterns tend to persist, even in dynamic computations*
- So, recent past is a good predictor of near future

In spite of increase in irregularity and adaptivity, this principle still applies at exascale, and is our main friend.

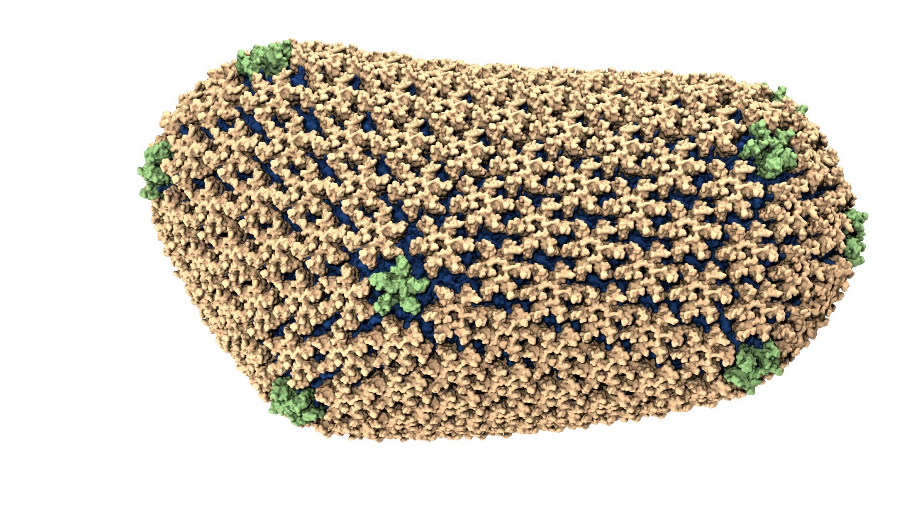
Measurement-based Load Balancing



XMAPP ideas and features have been demonstrated in full-scale production Charm++ applications

NAMD: Biomolecular simulations

- Collaboration with K. Schulten
- With over 45,000 registered users
- Scaled to most top US supercomputers
- In production use on supercomputers and clusters and desktops
- Gordon Bell award in 2002



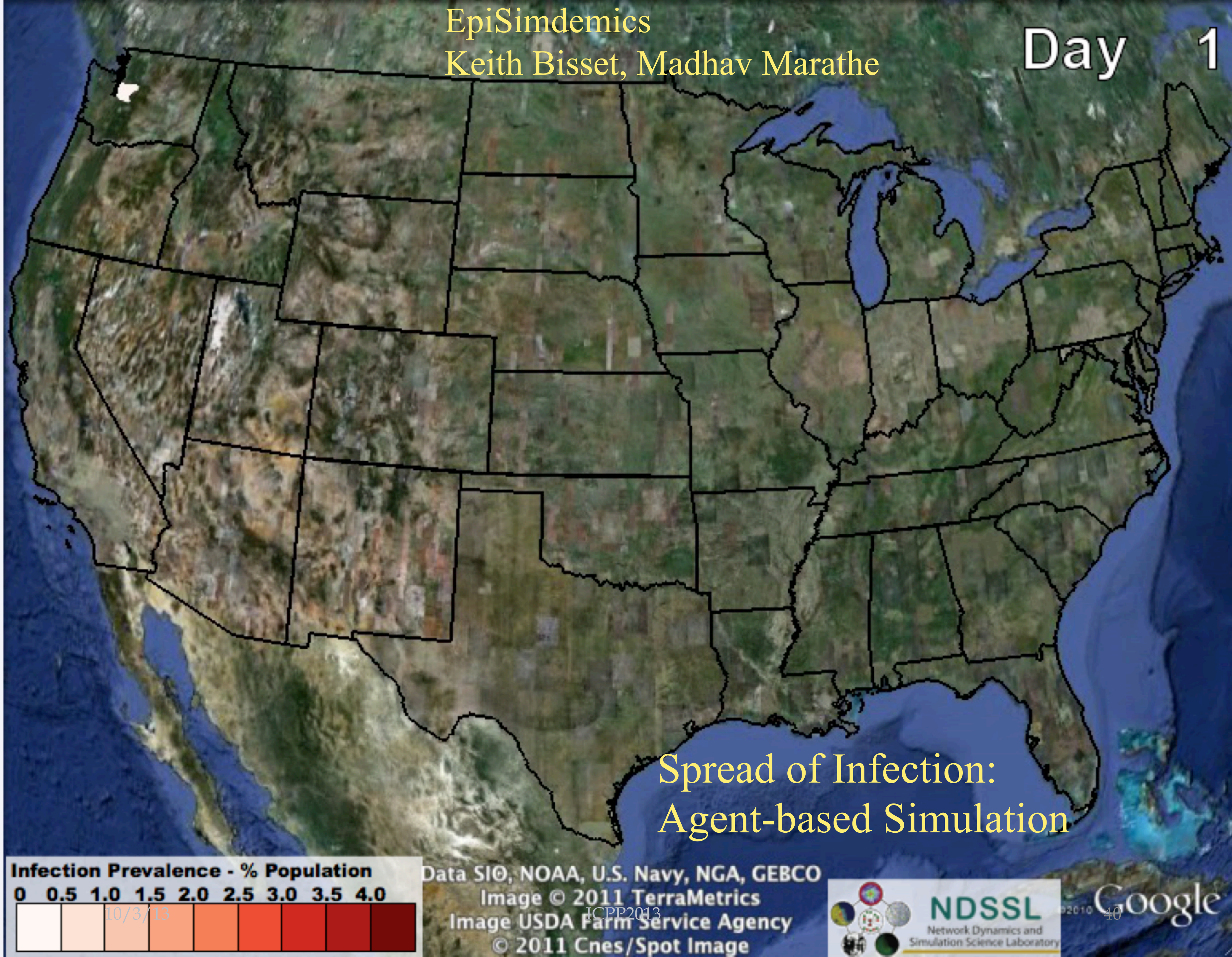
Recent success: Determination of the structure of HIV capsid by researchers including Prof Schulten

ChaNGa: Parallel Gravity

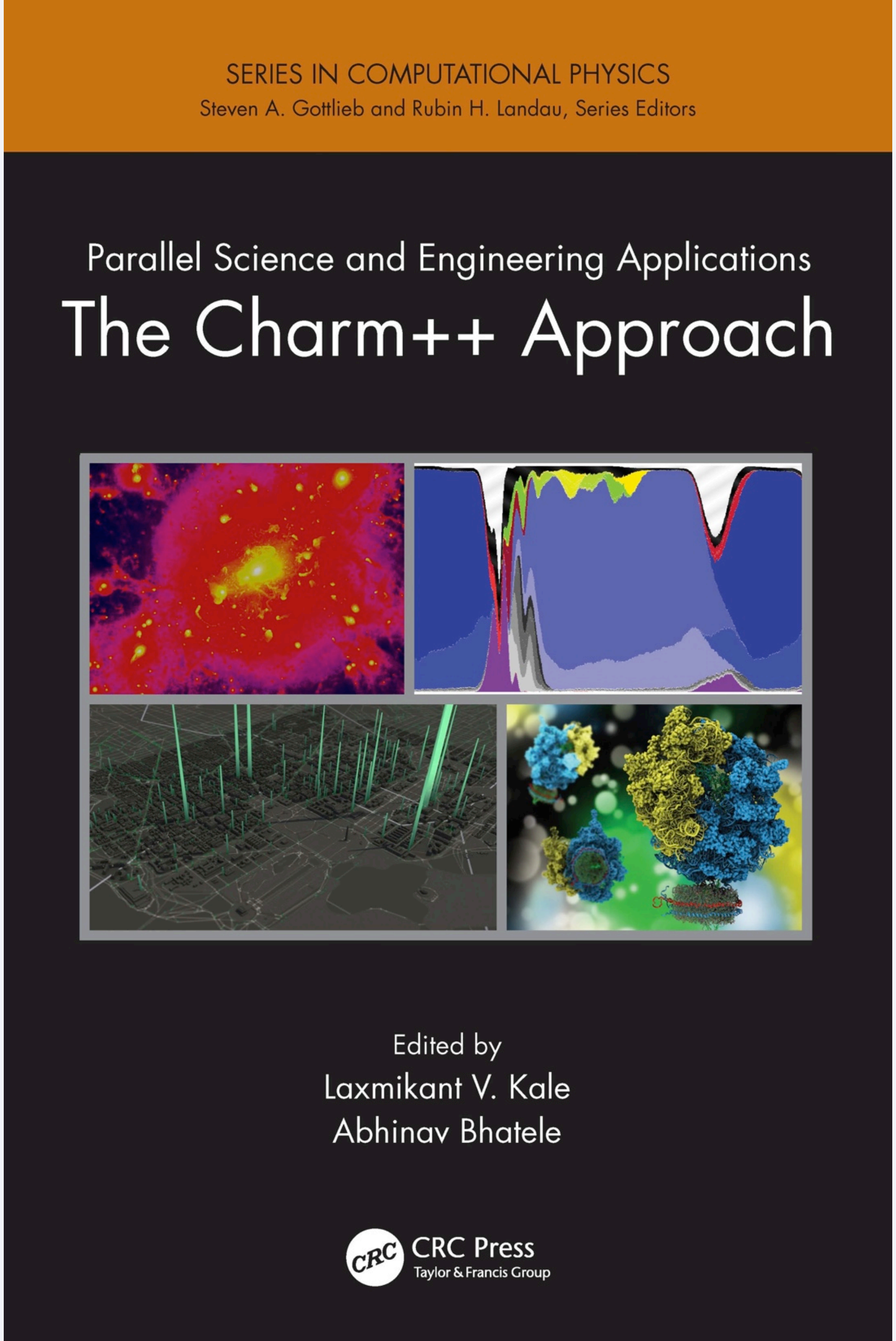
- Collaborative project (NSF)
  - with Tom Quinn, Univ. of Washington
- Gravity, gas dynamics
- Barnes-Hut tree codes
  - Oct tree is natural decomp
  - Geometry has better aspect ratios, so you "open" up fewer nodes
  - But is not used because it leads to bad load balance
  - Assumption: one-to-one map between sub-trees and PEs
  - Binary trees are considered better load balanced

Evolution of Universe and Galaxy Formation

With Charm++: use Oct-Tree, and let Charm++ map subtrees to processors


EpiSimdemics
Keith Bisset, Madhav Marathe
Day 1
Spread of Infection:
Agent-based Simulation
Infection Prevalence - % Population
0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2011 TerraMetrics
Image USDA Farm Service Agency
© 2011 Cnes/Spot Image
NDSSL
Network Dynamics and Simulation Science Laboratory
Google

An upcoming book Surveys seven major applications developed using Charm++



Saving Cooling Energy

- Easy: increase A/C setting
  - But: some cores may get too hot
- So, reduce frequency if temperature is high
  - Independently for each core or chip
- *But,* this creates a load imbalance!
- No problem, we can handle that
  - Migrate objects away from the slowed-down procs
  - Balance load using an existing strategy
  - Strategies take speed of processors into account
- Implemented in experimental version
  - SC 2011 paper, IEEE TC paper
- Several new power/energy-related strategies
  - PASA '12: Exploiting differential sensitivities of code segments to frequency change

Fault Tolerance in Charm++/AMPI

- Four Approaches:
  - Disk-based checkpoint/restart
  - In-memory double checkpoint/restart
  - Proactive object migration
  - Message-logging *with parallel restart*: scalable fault tolerance
- Common Features:
  - Leverages object-migration capabilities
  - Based on dynamic runtime capabilities
- Several new results in the last year:
  - FTXS 2012: scalability of in-mem scheme
  - Hiding checkpoint overhead .. with semi-blocking..
  - Energy efficiency of FT protocols : best paper SBAC-PAD

Ships in Charm++ distribution, for years

Another idea for increasing controllable variables:

Reconfigurable Applications

App based Creation of Control Points

- A richer set of control points can be generated if we enlist help from the application
  - Or its DSL runtime, or compiler
- The idea is:
  - Application exposes some control knobs
  - Describes the effects of the knobs
  - The RTS observes performance variables, identifies the knobs that will help the most, and turns them in the right direction
- Examples: granularity, yield frequencies in inner loops, CPU-Accelerator balance

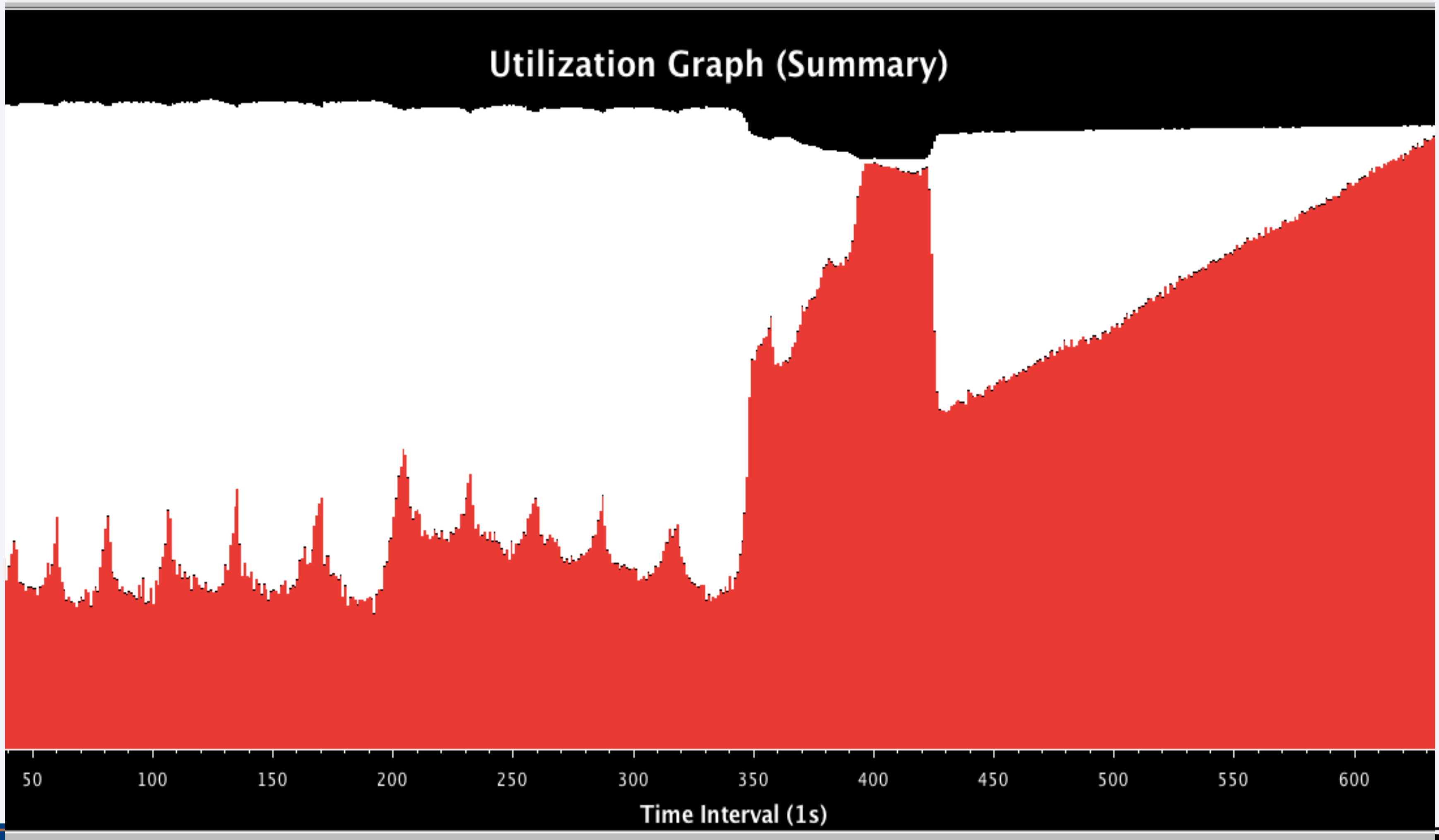
Load Balancing Framework

- Charm++ load balancing framework is an example of "customizable" RTS
- Which strategy to use, and how often to call it, can be decided for each application separately
- But if the programmer exposes one more control point, we can do more:
  - Control point: iteration boundary
  - User makes a call each iteration saying they can migrate at that point
  - Let us see what we can do: metabalancer

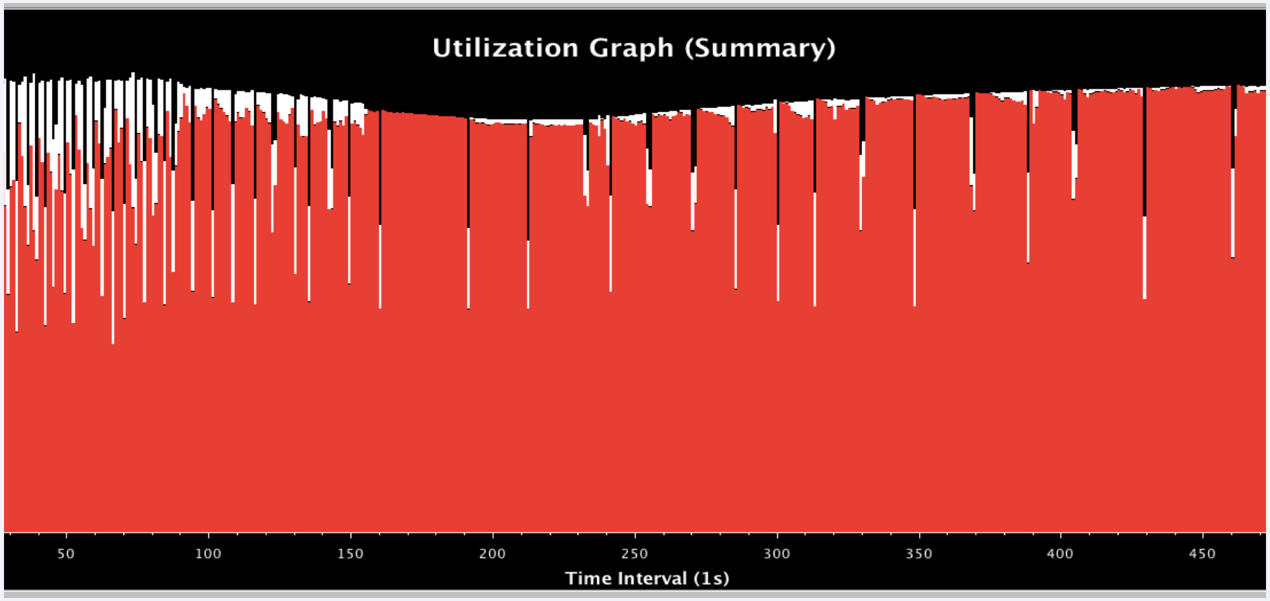
Meta-Balancer

- Automating load balancing related decision making
- Monitors the application continuously
  - Asynchronous collection of minimum statistics
- Identifies when to invoke load balancing for optimal performance based on
  - Predicted load behavior and guiding principles
  - Performance in recent past

Fractography: Without LB



Meta-Balancer on Fractography



- Identifies the need for frequent load balancing in the beginning
- Frequency of load balancing decreases as load becomes balanced
- Increases overall processor utilization and gives gain of 31%

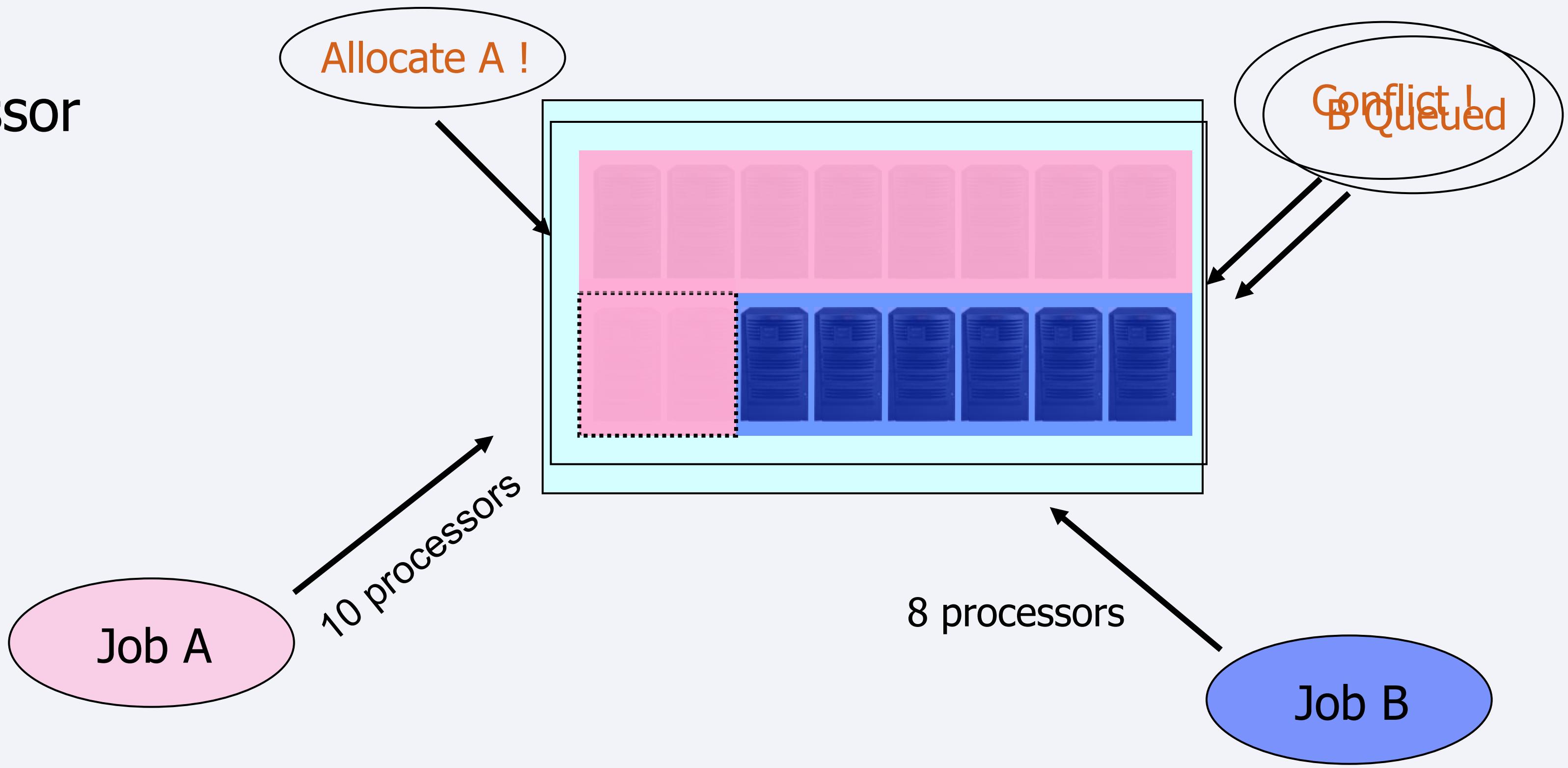
Shrink/Expand job

- If a job is told to reduce the number of nodes it is using..
- It can do so now by migrating objects..
- Same with expanding the set of nodes used
- Empowered by migratability

Inefficient Utilization within a cluster

16 Processor system

- Job A
- Job B



Current Job Schedulers can lead to low system utilization !

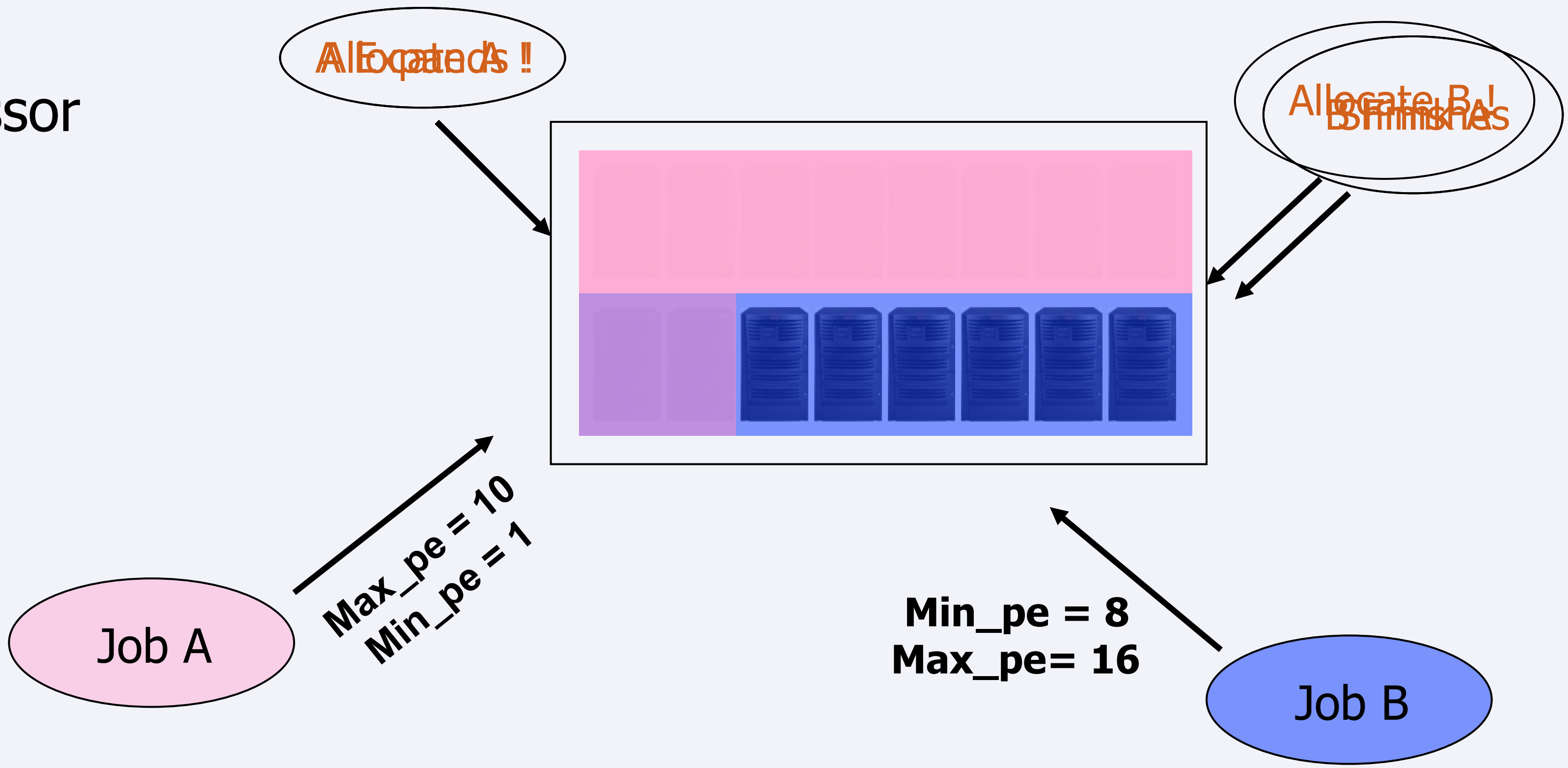
Adaptive Job Scheduler

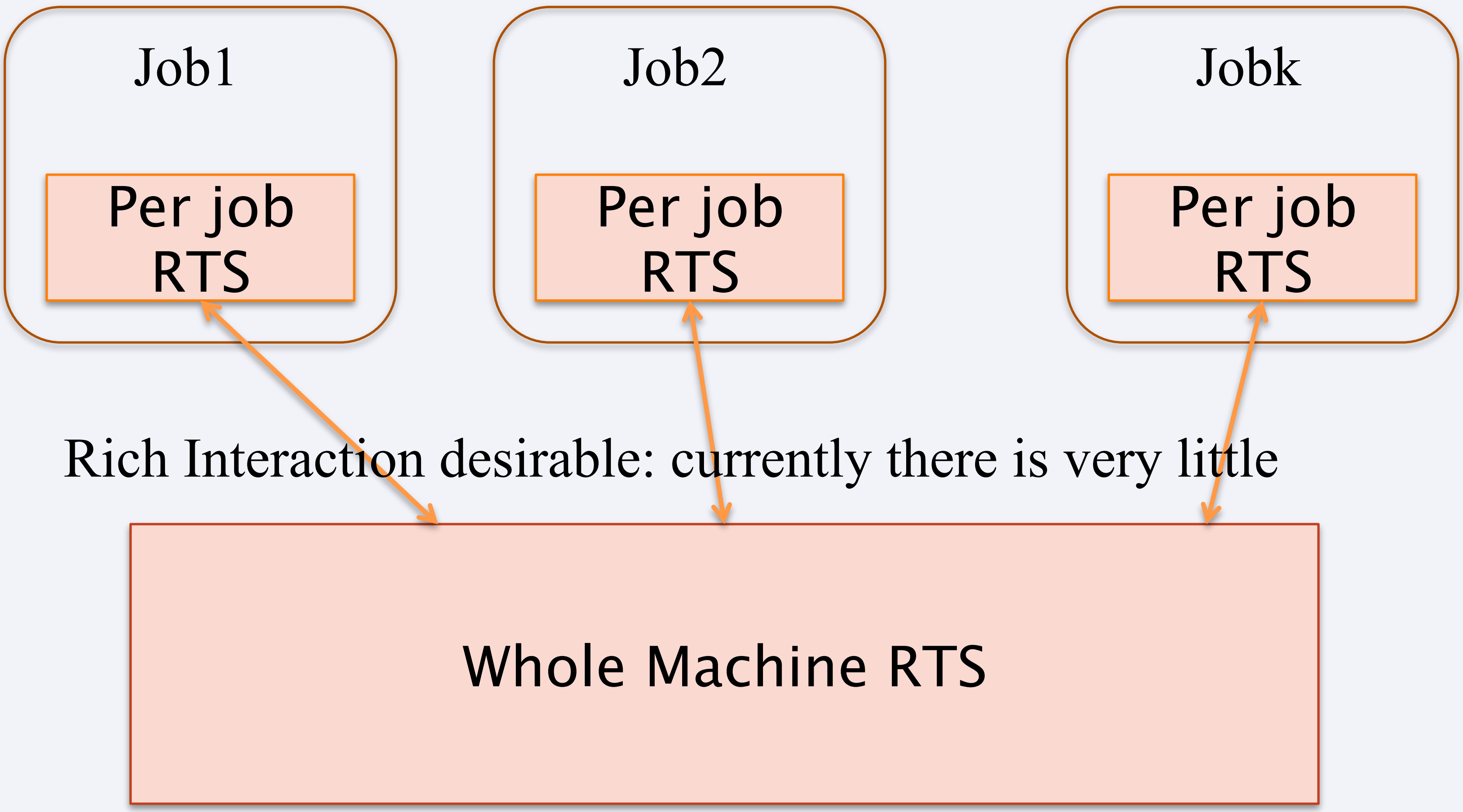
- Scheduler can take advantage of the adaptivity of XMAPP jobs
- Improve system utilization and response time
- Scheduling decisions
  - Shrink existing jobs when a new job arrives
  - Expand jobs to use all processors when a job finishes
- Processor map sent to the job
  - Bit vector specifying which processors a job is allowed to use
    - 00011100 (use 3 4 and 5!)
- Handles regular (non-adaptive) jobs

Two Adaptive Jobs

16 Processor system

- Job A
- Job B




Job1
Per job RTS
Job2
Per job RTS
Jobk
Per job RTS
Rich Interaction desirable: currently there is very little
Whole Machine RTS

Whole machine runtime

- Job schedulers and resource allocators:
  - Accept more flexible QoS specifications from jobs
    - Creating more control variables
  - “moldable” specification:
    - This job needs between 3000-5000 nodes
    - Memory requirements..
    - Topology sensitivity, speedup profiles,…
  - Malleable:
    - this job can be told to shrink/expand after it has started

Whole machine control

- Monitor failures, and act in job-specific ways
- Global power constraints:
  - Inform, negotiate with and constrain jobs
- Thermal management
- I/O system and job I/O interactions
- Shrink and Expand jobs as needed to optimize multiple metrics

Novel, Revolutionary and Old?

- These concepts have been around for a while
  - E.g. Charm++ even in the present form is 13-15 years old
- An analogy might help

Dinosaurs, mammals and primates

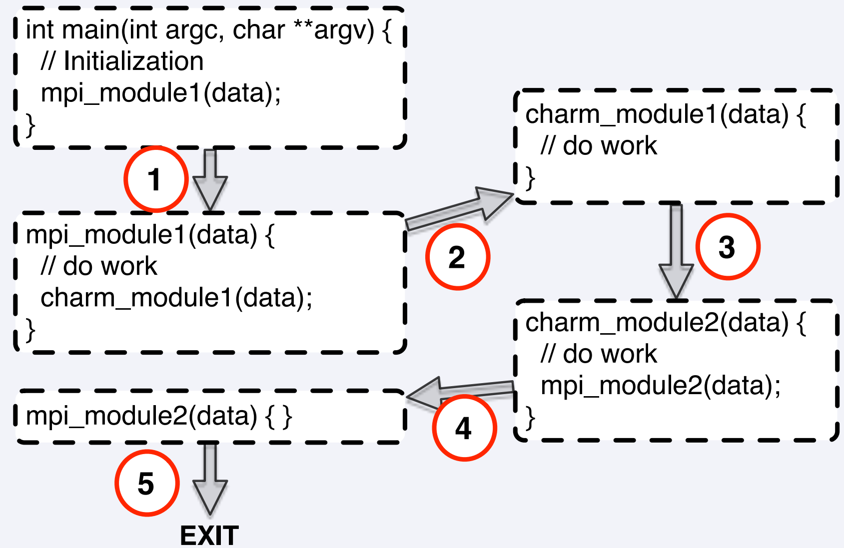
- When the asteroid created a shock to the ecosystem
  - For us, multiple asteroids together:
    - End of frequency scaling,
    - Complex heterogeneous hardware,
    - Thermal, power, energy issues,
    - Component failures
    - increasingly complex apps
  - Dinosaurs (well.. MPI) and mammals (XMAPP) both existed
    - But dinosaurs died out, mammals survived, and evolved further
    - The premium on "smart" rather than "big" in the ecosystem eventually saw the emergence of humans
      - Well.. Bending the truth a bit for the sake of analogy
    - Well, dinosaurs survived as birds… maybe MPI 5?

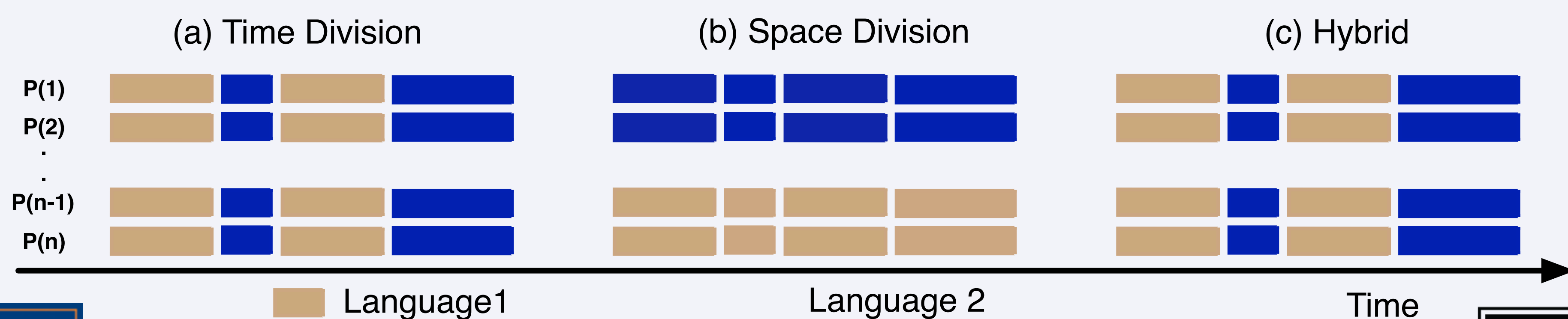
XMAPP models: adoption

- It is challenging to get the community to adopt a new programming model
  – And here we are talking about a whole class of them!
- It helps
  – To get a few from-scratch success stories
  – Some apps may get "refactored" to use the new model (Episimdemics)
- But large-scale adoption will be helped if we can support true "interoperability"

Interoperation of Parallel Languages

- Implement a library in the language that suits it the most, and use them together!
- MPI + UPC, MPI + OpenMP + Charm++





Is Interoperation Feasible in Production Applications?

Application	Library	Productivity	Performance
CHARM in MPI (on Chombo)	HistSort in Charm++	195 lines removed	48x speed up in Sorting
EpiSimdemics	MPI IO	Write to single file	256x faster input
NAMD	FFTW	280 lines less	Similar performance
Charm++'s Load Balancing	ParMETIS	Parallel graph partitioning	Faster applications

Conclusions

- We need a much richer control system
  - For each parallel job
  - For parallel machine as a whole
- Current status: paucity of control variables
- Programming models can help create new observable and controllable variables
- As far as I can see,
  - XMAPP class programming models,
  with overdecomposition and migratability, and
  the resultant asynchrony and adaptivity
  are the main vehicle for this..
  - Do you see other ideas?

Conclusion

- HPC community suggestions:
  - Develop new XMAPP models
    - But: make sure you develop it in the context of at least two reasonable-size applications
  - Collaborate and compete on runtime adaptation strategies, based on the common assumptions of XMAPP models
    - Possibly develop standards for mature pieces

I am looking for a postdoc and/or a research programmer

See you at Charm++ BOF at SC: Tuesday noon

More info on Charm++: http://charm.cs.illinois.edu