Composable and modular Exascale Programming Models with intelligent runtime systems:

To Virtualize or Not?!
Of course, virtualize

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Observations: exascale machines

- Just restating, with a bit of my take added
- Many (1000+) cores in a "node"
- Heterogeneous cores:
  - specialization saves energy
  - Possibly reconfigurable hardware
- Main reason for accelerators:
  - "cache" idea had outlived its utility
  - So: explicit control over data movement
    - Scratchpad memories a la Cell, GPGPU, ..
  - Hardware context switches for tolerating latency
- Communication challenges: variable speeds?

Application Segmentation

- We may have to specialize architectures to classes of applications
  - Two dimensions: memory-per-core, bisection bandwidth
  - Of the 4 quadrants formed, more than 1 are populated by real apps, I think
  - We can design *very* different machines for each class
    - E.g. For many apps we may need to go to a machine design with (say) no external DRAM. Use all the pins for communication.., and say use a simple grid network.
- We need a serious study of applications
  - Emphasizing exascale problem instances
  - Use something like BigSim to do parametric studies to quantify needs of application

Observations: Exascale applications

- Development of new models must be driven by the needs of exascale applications
  - Multi-resolution
  - Multi-module (multi-physics)
  - Dynamic/adaptive : to handle application variation
  - Adapt to a volatile computational environment
  - Exploit heterogeneous architecture
- So? Consequences:
  - Must support automated resource management
  - Must support interoperability and parallel composition

Decomposition Challenges

- Current method is to decompose to processors
  - But this has many problems
  - deciding which processor does what work in detail is difficult at large scale
- Decomposition should be independent of number of processors
  - Our design principle since early 1990’s
    - (in Charm++ and AMPI)

Processors vs “WUDU”s

- Eliminate “processor” from programmer’s vocabulary
  - Well, almost
- Decomposition into:
  - Work-Units and Data Units (WUDUs)
  - Work-units: code, one or more data units
  - Data-units: sections of arrays, meshes, ..
  - Amalgams:
    - Objects with associated work-units,
    - Threads with own stack and heap
- Who does decomposition?
  - Programmer, compiler, or both

Different kinds of units

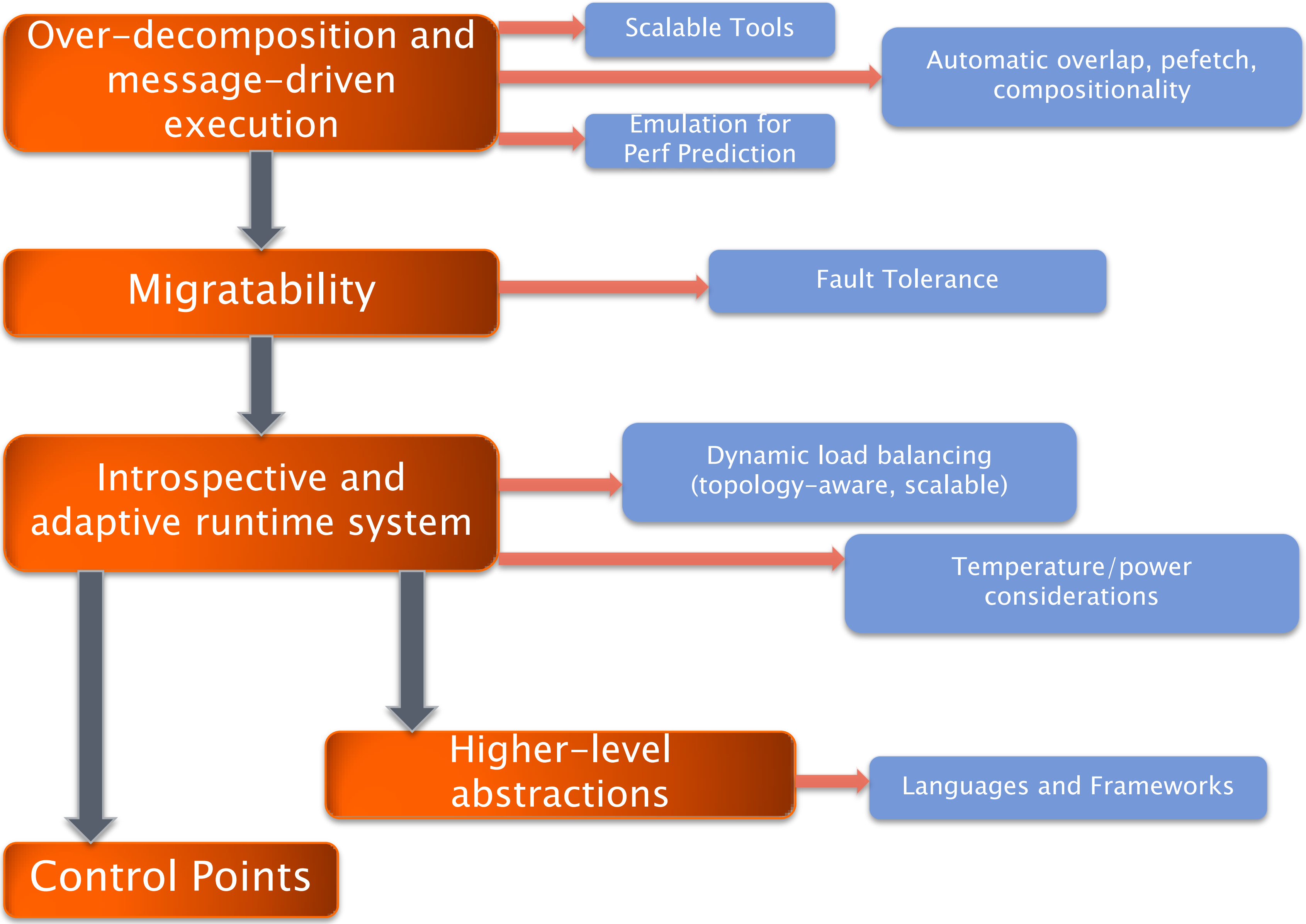
- Migration units:
  - objects, migratable threads (i.e. “processes”), data sections
- DEBs: units of scheduling
  - Dependent Execution Block
  - Begins execution after one or more (potentially) remote dependence is satisfied
- SEBs: units of analysis
  - Sequential Execution Blocks
  - A DEB is partitioned into one or more SEBs
  - Has a “reasonably large” granularity, and uniformity in code structure
  - Loop nests, functions, ..

Migratable objects programming model

- Names for this model:
  - Overdecompostion approach
  - Object-based overdecomposition
  - Processor virtualization
  - Migratable-objects programming model

Empower Adaptive Runtime System

- Decomposing program into a large number of WUDUs empowers the RTS, which can:
  - Migrate WUDUs at will
  - Schedule DEBS at will
  - Instrument computation and communication at the level of these logical units
    - WUDU x communicates y bytes to WUDU z every iteration
    - SEB A has a high cache miss ratio
  - Maintain historical data to track changes in application behavior
    - E.g. to trigger load balancing



Over-decomposition and message-driven execution

Scalable Tools

Automatic overlap, pefetch, compositionality

Emulation for Perf Prediction

Migratability

Fault Tolerance

Introspective and adaptive runtime system

Dynamic load balancing (topology-aware, scalable)

Temperature/power considerations

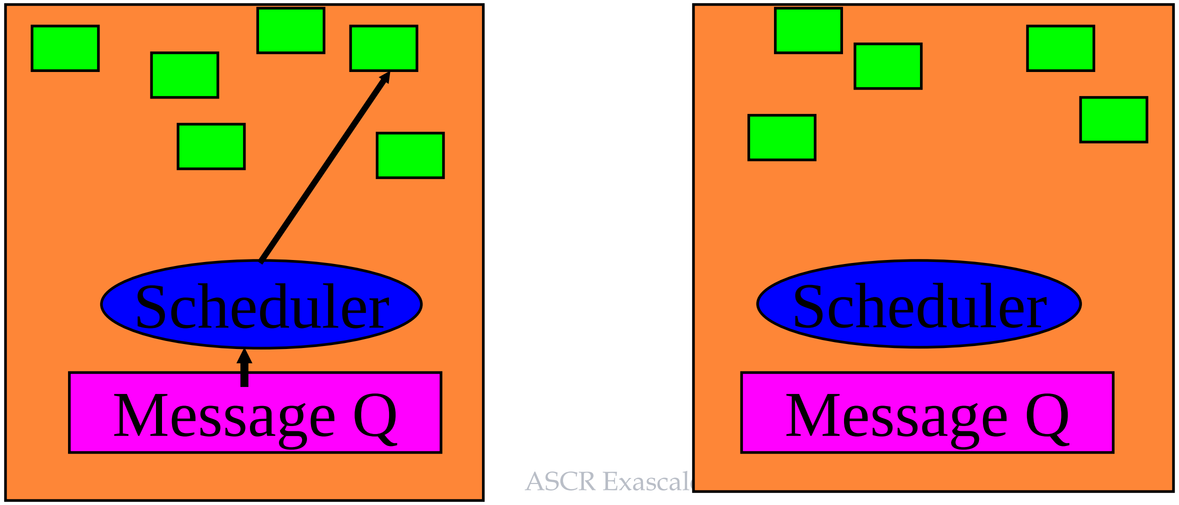
Higher-level abstractions

Languages and Frameworks

Control Points

Utility for Multi-cores, Many-cores, Accelerators:

- Objects connote and promote locality
- Message-driven execution
  - A strong principle of prediction for data and code use
  - Much stronger than principle of locality
    - Can use to scale memory wall:
    - Prefetching of needed data:
      - into scratch pad memories, for example



Impact on communication

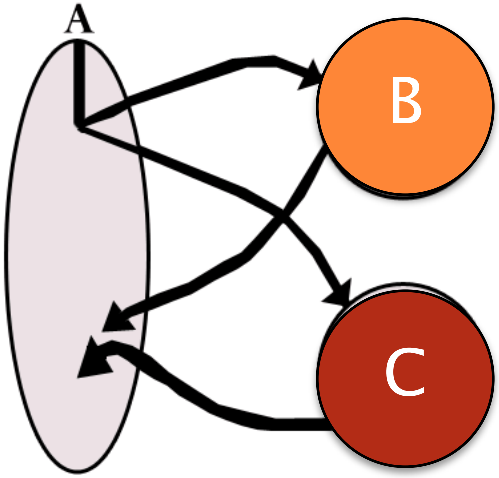
- Current machines are over-engineered for communication by necessity:
  - Compute-communicate cycles in typical MPI apps
  - So, the network is used for a fraction of time,
  - and is on the critical path
- With overdecomposition (virtualization)
  - Communication is spread over an iteration
  - Also, adaptive overlap of communication and computation

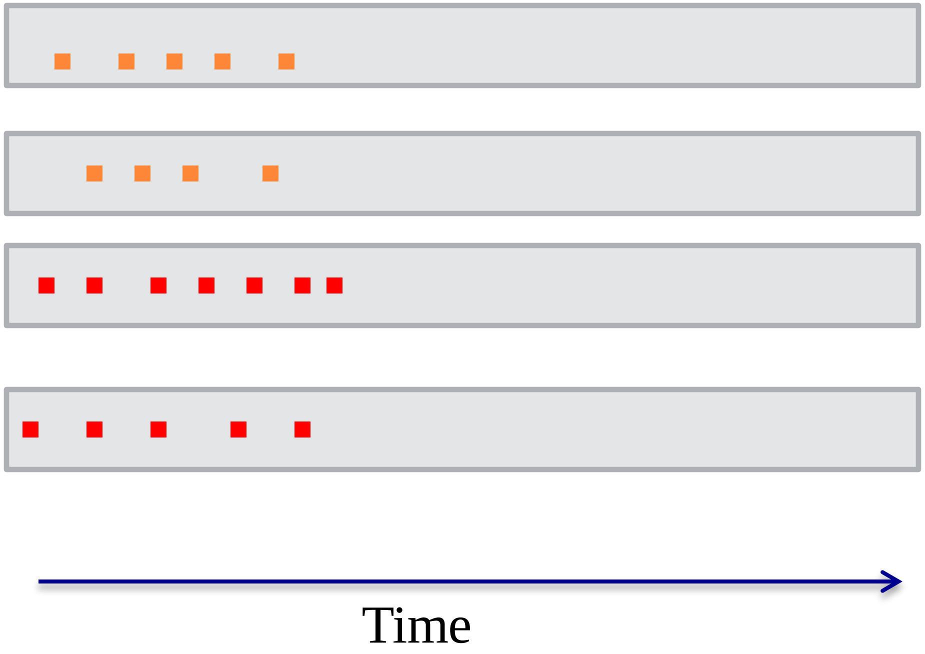
Compositionality

- It is important to support parallel composition
  - For multi-module, multi-physics, multi-paradigm applications..
- What I mean by parallel composition
  - B || C where B and C are independently developed modules
  - B is parallel module by itself, and so is C
  - Programmers who wrote B were unaware of C
- This is not supported well by MPI
  - Developers support it by breaking abstraction boundaries
    - E.g. wildcard recvs in module A to process messages for module B
  - Nor by OpenMP implementations :

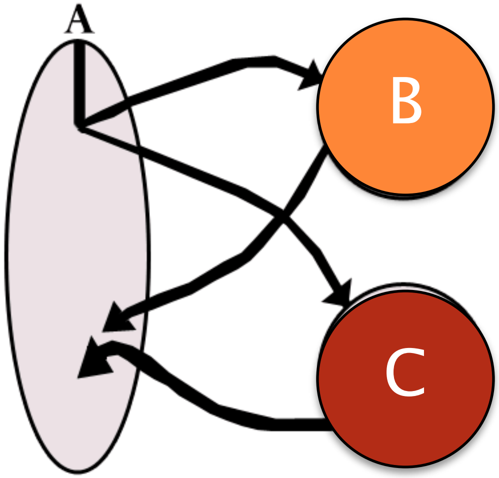
Without message-driven execution (and virtualization), you get either:

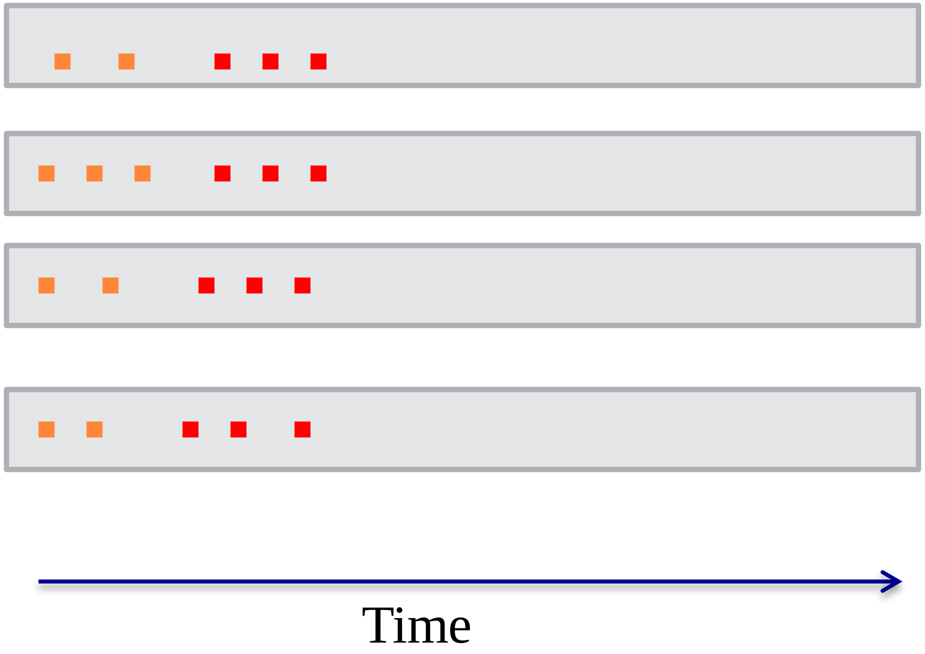
Space-division



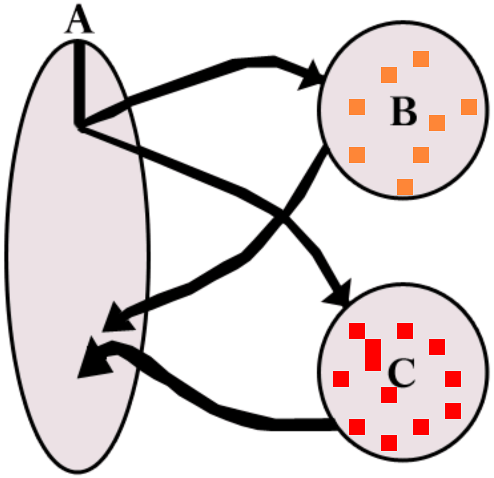


OR: Sequentialization





Parallel Composition: A1; (B || C); A2

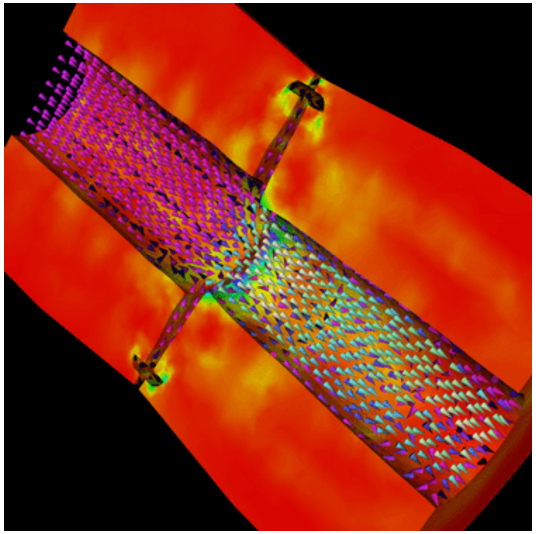


Recall: Different modules, written in different languages/paradigms, can overlap in time and on processors, without programmer having to worry about this explicitly

Decomposition Independent of numCores

- Rocket simulation example under traditional MPI

Solid | Solid | . . . | Solid
Fluid | Fluid | | Fluid
1 | 2 | | P



- With migratable-objects:

Solid$_1$ Solid$_2$ Solid$_3$ . . . Solid$_n$

Fluid$_1$ Fluid$_2$ . . . Fluid$_m$

  – Benefit: load balance, communication optimizations, modularity

Load Balancing

- Static
  - Irregular applications
  - Programmer shouldn't have to figure out ideal mapping
- Dynamic:
  - Applications are increasingly using adaptive strategies
  - Abrupt refinements
  - Continuous migration of work: e.g. particles in MD
- Challenges:
  - Performance limited by most overloaded processor
  - The chance that one processor is severely overloaded gets higher as #processors increases

Migratable Objects Empower Automated Load Balancing!

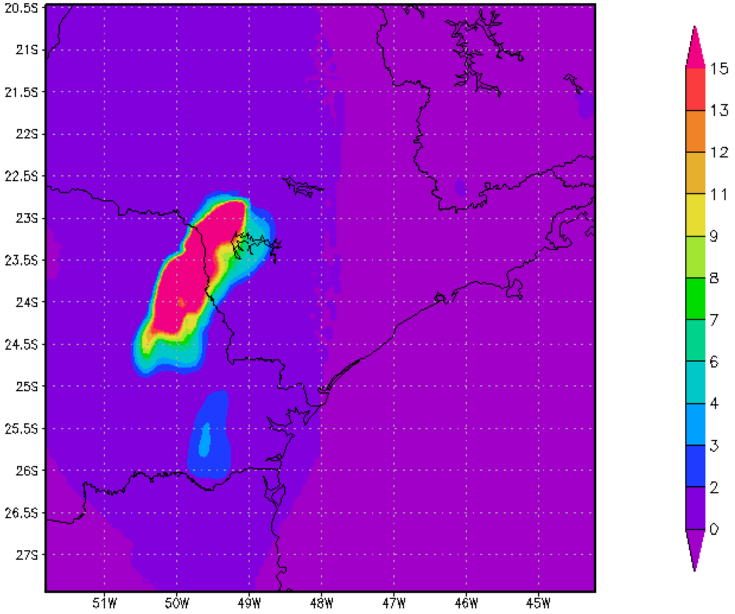
Principle of Persistence

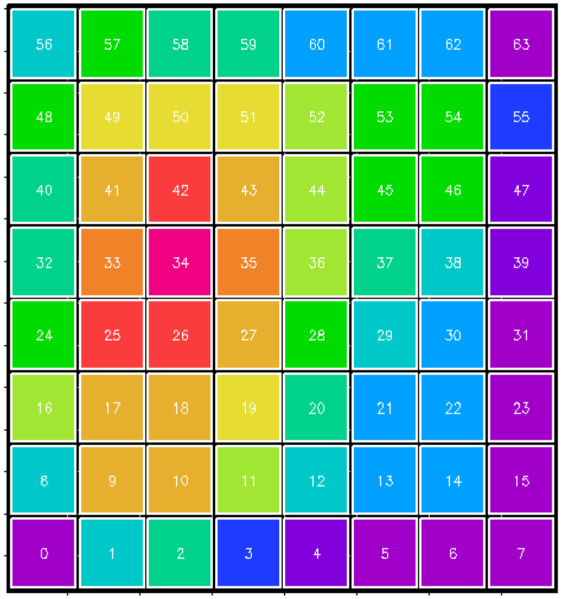
- Once the computation is expressed in terms of its natural (migratable) objects
- *Computational loads and communication patterns* <u>*tend to*</u> *persist, even in dynamic computations*
- So, recent past is a good predictor of near future

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

A quick Example:
Weather Forecasting in BRAMS

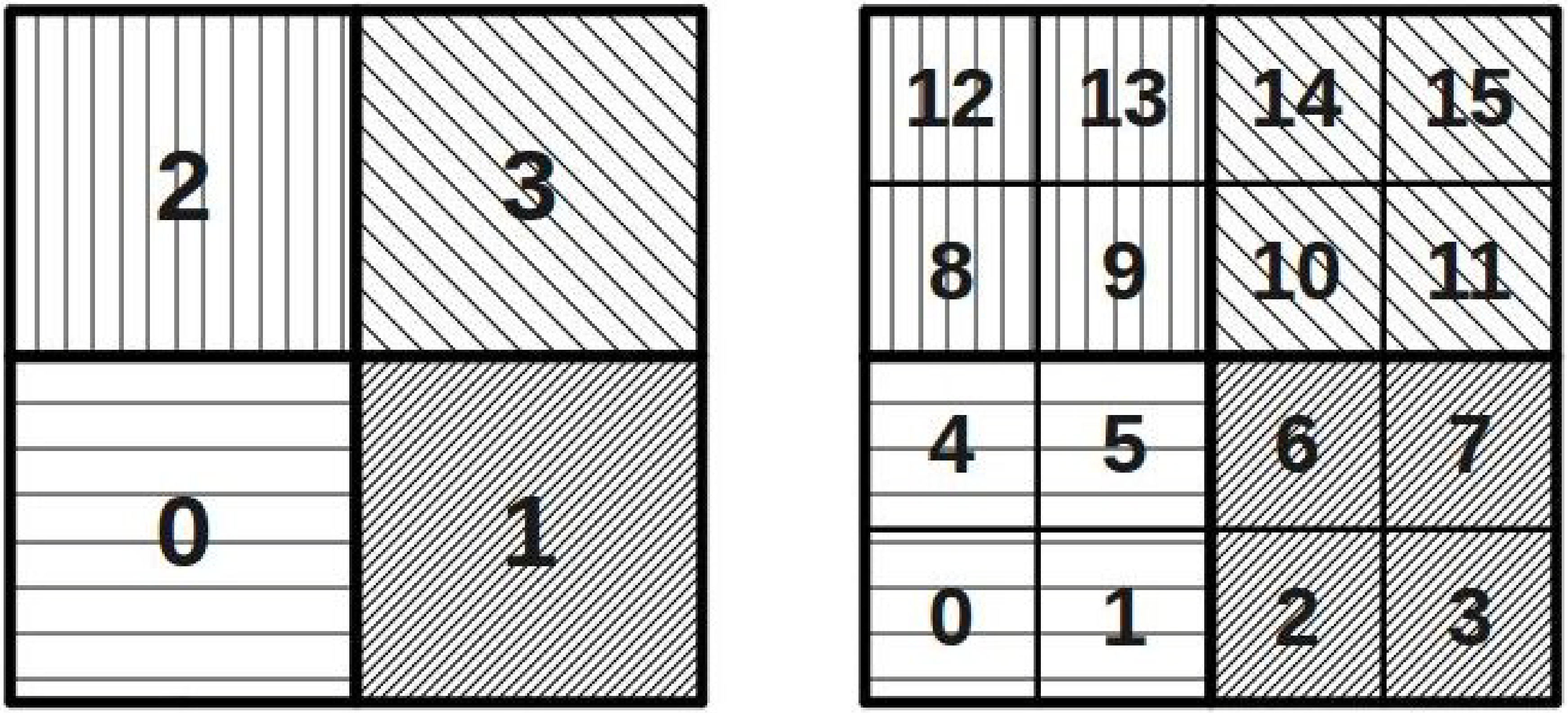
- Brams: Brazillian weather code (based on RAMS)
- AMPI version (Eduardo Rodrigues, with Mendes and J. Panetta)

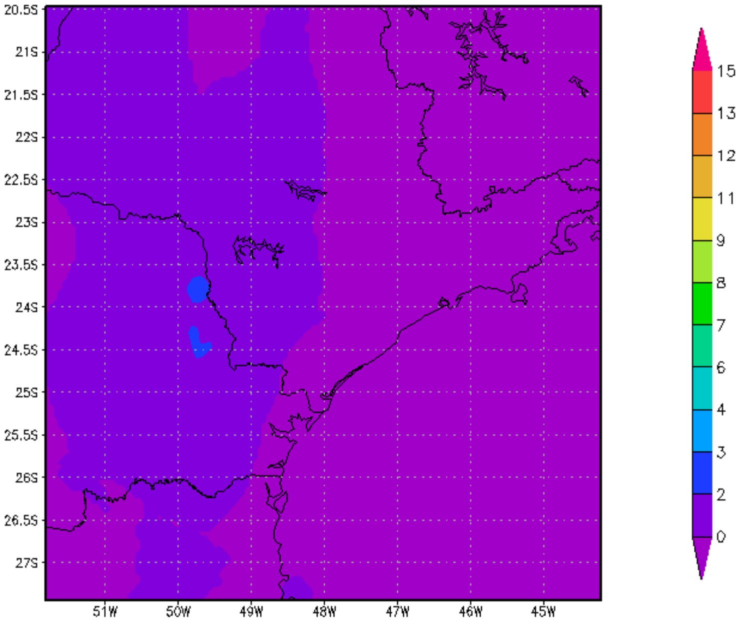




56	57	58	59	60	61	62	63
48	49	50	51	52	53	54	55
40	41	42	43	44	45	46	47
32	33	34	35	36	37	38	39
24	25	26	27	28	29	30	31
16	17	18	19	20	21	22	23
8	9	10	11	12	13	14	15
0	1	2	3	4	5	6	7

Basic Virtualzation of BRAMS





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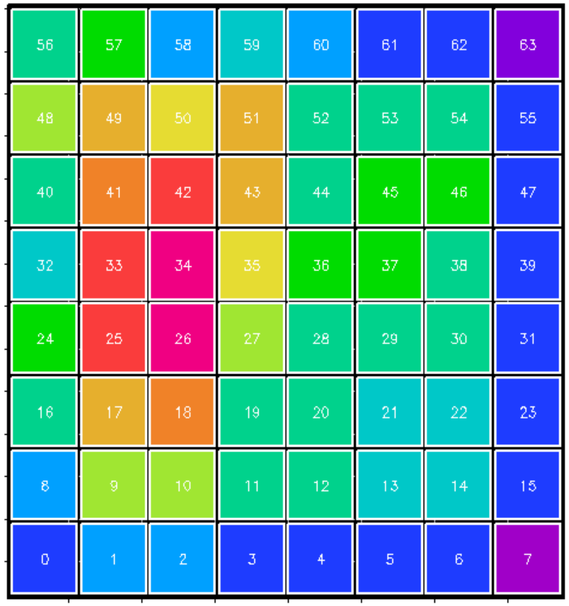

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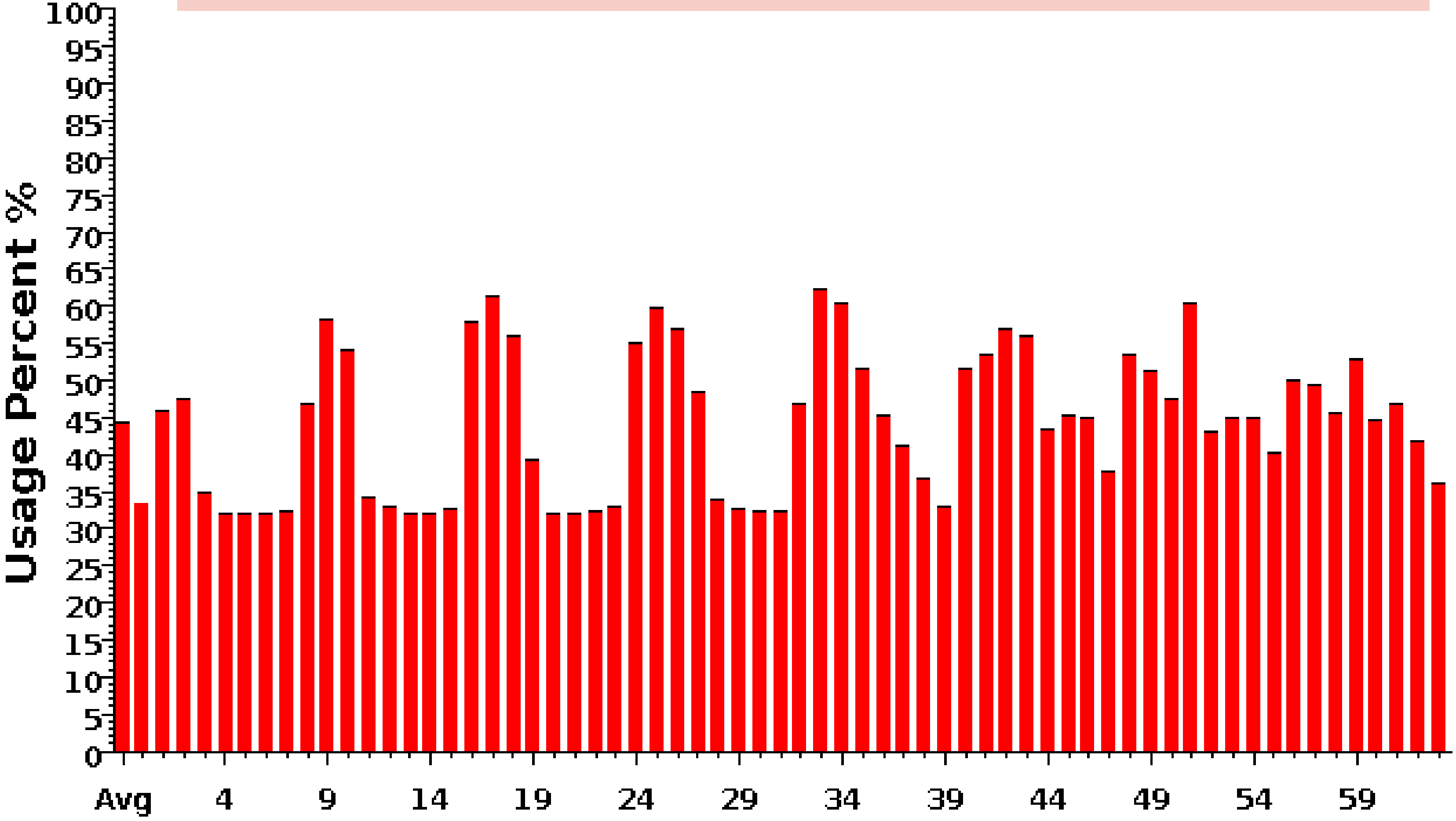
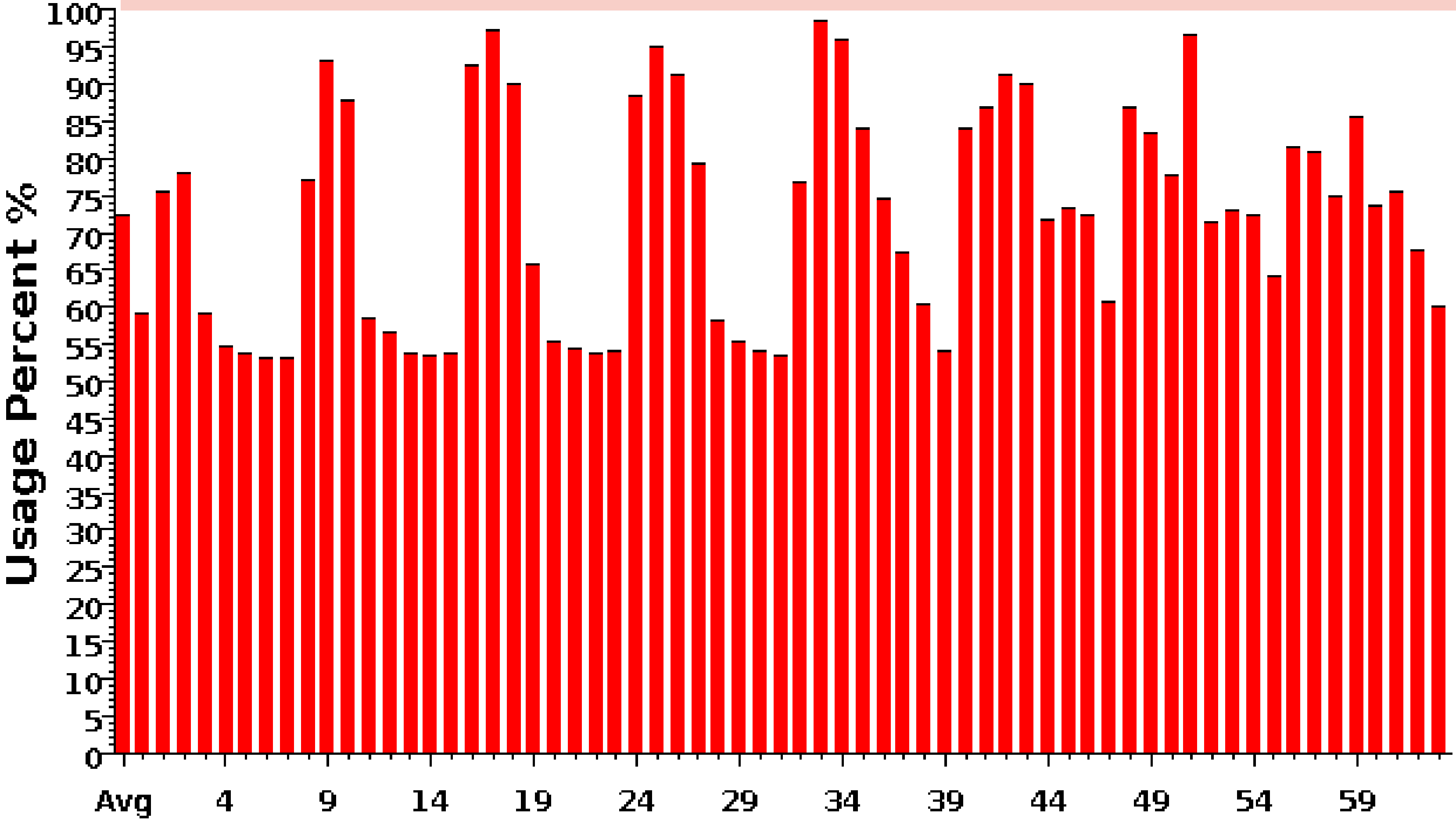
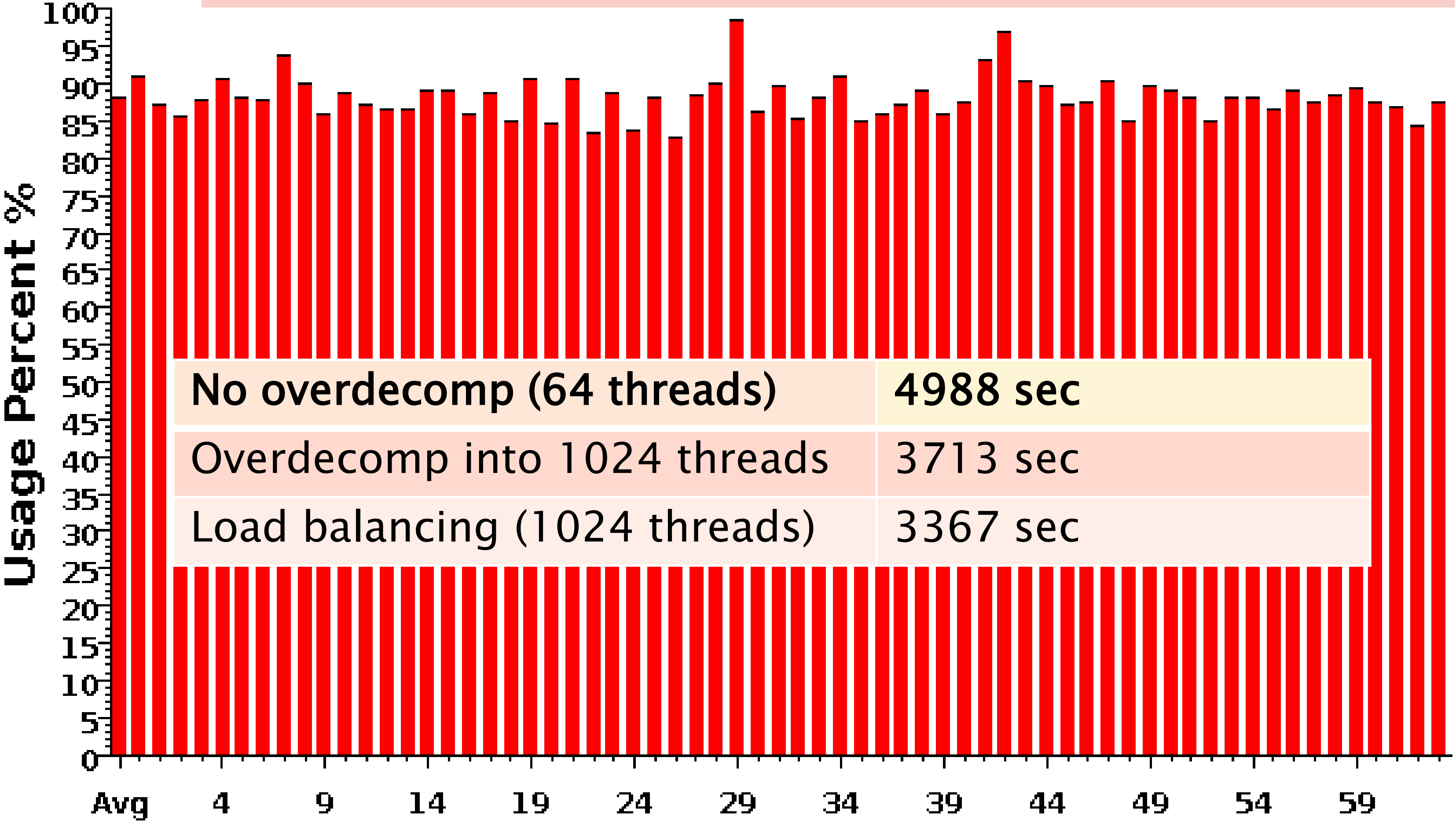
Baseline: 64 objects on 64 processors



Over-decomposition: 1024 objects on 64 processors: Benefits from communication/computation overlap



With Load Balancing:
1024 objects on 64 processors



No overdecomp (64 threads)	**4988 sec**
Overdecomp into 1024 threads	3713 sec
Load balancing (1024 threads)	3367 sec

Load Balancing for Large Machines: I

- Centralized balancers achieve best balance
  - Collect object-communication graph on one processor
  - But won't scale beyond tens of thousands of nodes
- Fully distributed load balancers
  - Avoid bottleneck but… Achieve poor load balance
  - Not adequately agile
- Hierarchical load balancers
  - Careful control of what information goes up and down the hierarchy can lead to fast, high-quality balancers
- Need for a universal balancer that works for all applications

Load Balancing for Large Machines: II

- Interconnection topology starts to matter again
  - Was hidden due to wormhole routing etc.
  - Latency variation is still small
  - But bandwidth occupancy is a problem
- Topology aware load balancers
  - Some general heuristic have shown good performance
    - But may require too much compute power
  - Also, special-purpose heuristic work fine when applicable
  - Still, many open challenges

Dealing with Thermal Variation

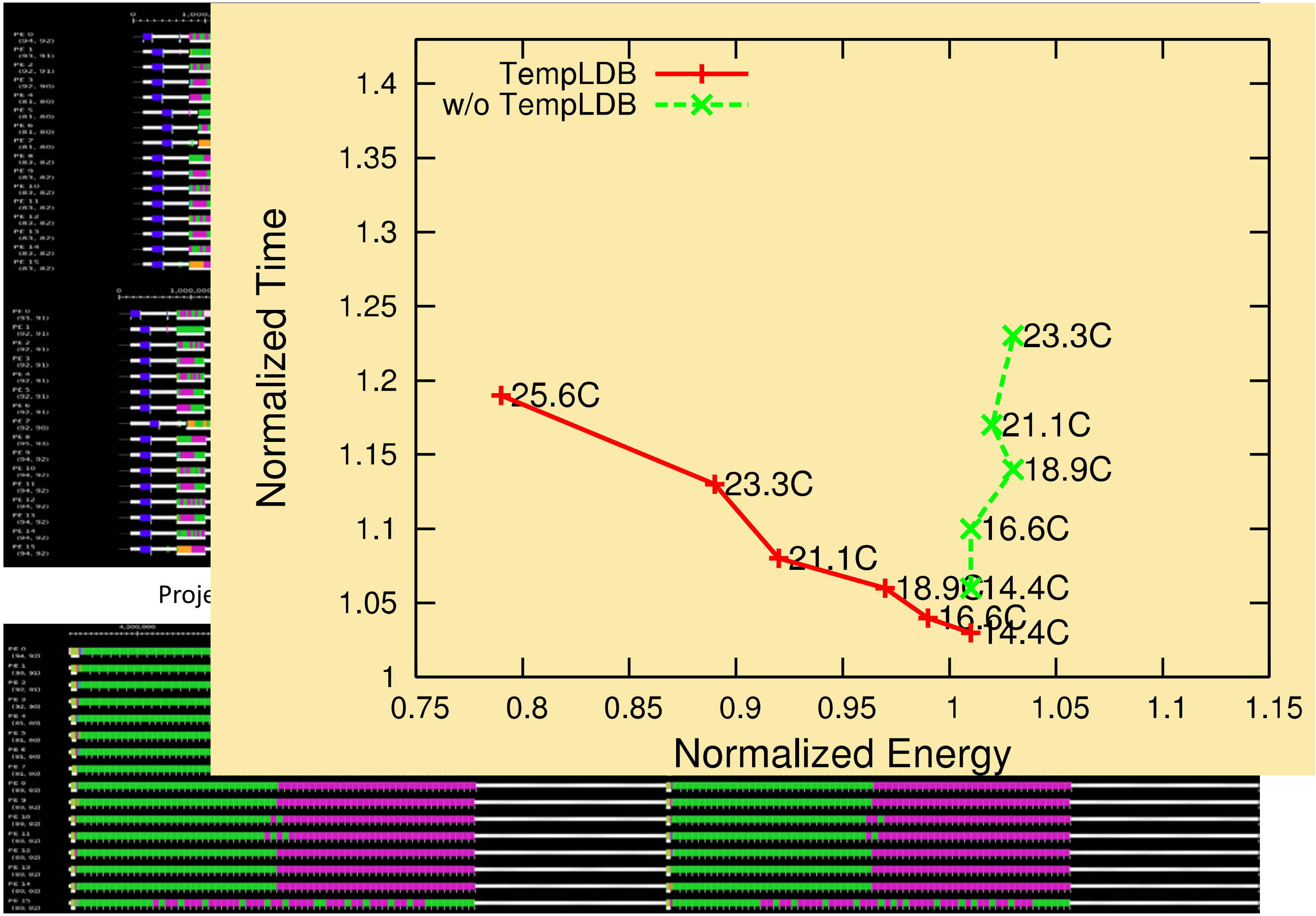
- Some cores/chips might get too hot
  - We want to avoid
    - Running everyone at lower speed,
    - Conservative (expensive) cooling
- Reduce frequency (DVFS) of the hot cores?
  - Works fine for sequential computing
  - In parallel:
    - There are dependences/barriers
    - Slowing one core down by 40% slows the whole computation by 40%!
      - Big loss when the #processors is large

Migratable Objects to the rescue!

Temperature-aware Load Balancing

- Reduce frequency if temperature is high
  - Independently for each core or chip
- Migrate objects away from the slowed-down processors
  - Balance load using an existing strategy
  - Strategies take speed of processors into account
- Recently implemented in experimental version
  - SC 2011 paper

Benefits of Temperature Aware LB

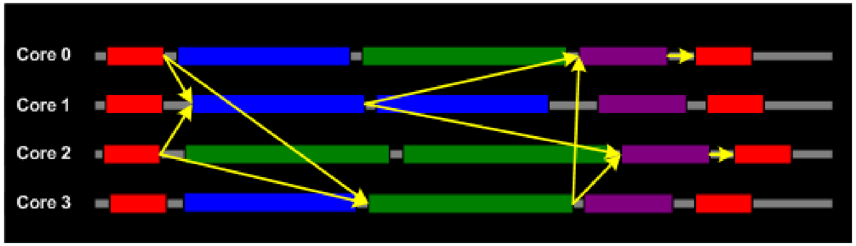


Proje

Zoomed projection timeline for two iterations without temperature aware LB

Other Power-related Optimizations

- Other optimizations are in progress:
  - Staying within given energy budget, or power budget
    - Selectively change frequencies so as to minimize impact on finish time
  - Reducing power consumed with low impact on finish time
    - Identify code segments (methods) with high miss-rates
      - Using measurements (principle of persistence)
    - Reduce frequencies for those,
    - and balance load with that assumption
  - Use critical paths analysis:
    - Slow down methods not on critical paths
    - Aggressive: migrate critical-path objects to faster cores



Scalable Fault tolerance

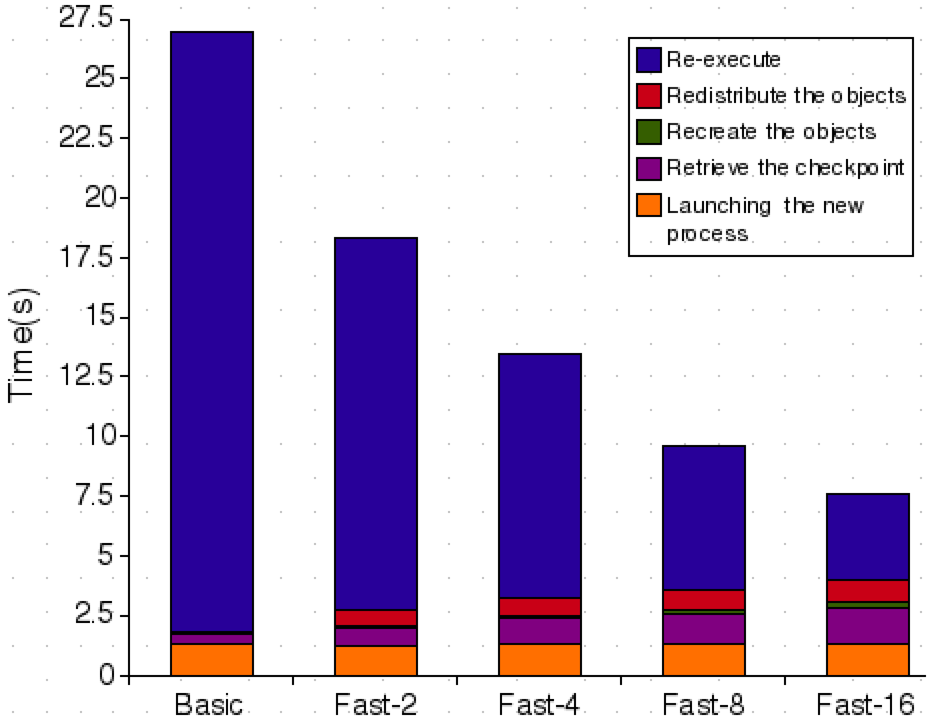
- Faults will be common at exascale
  - Failstop, and soft failures are both important
- Checkpoint-restart will not scale
  - Requires all nodes to roll back even when just one fails
    - Inefficient: computation and power
  - As MTBF goes lower, it becomes infeasible

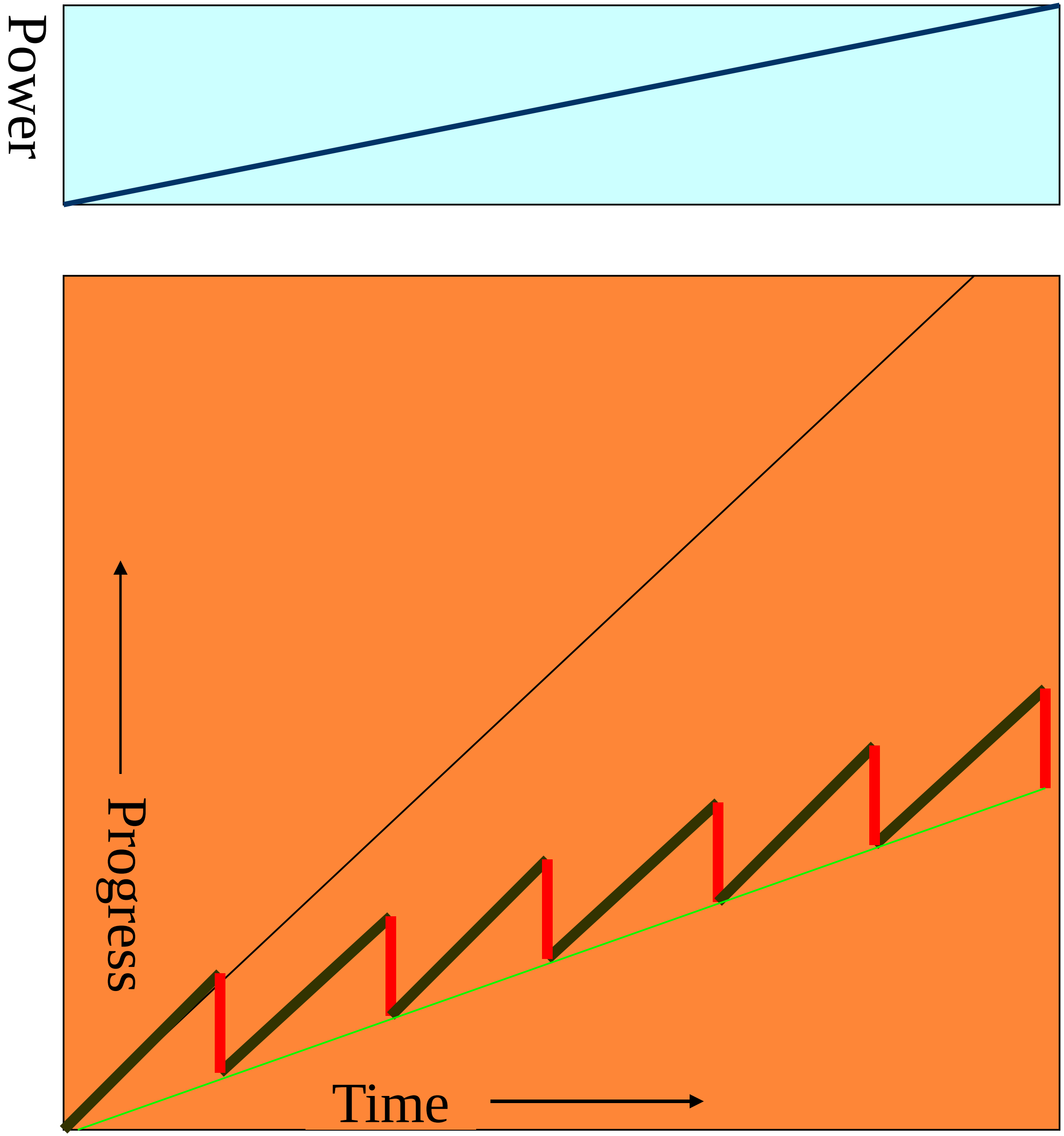
Message-Logging

- Basic Idea:
  - Messages are stored by sender during execution
  - Periodic checkpoints still maintained
  - After a crash, reprocess "recent" messages to regain state
- Does it help at exascale?
  - Not really, or only a bit: Same time for recovery!
- With virtualization,
  - work in one processor is divided across multiple virtual processors; thus, *restart can be parallelized*
  - Virtualization helps fault-free case as well

Message-Logging (cont.)

- Fast Parallel restart performance:
  - Test: 7-point 3D-stencil in MPI, P=32, 2 ≤ VP ≤ 16
  - Checkpoint taken every 30s, failure inserted at t=27s

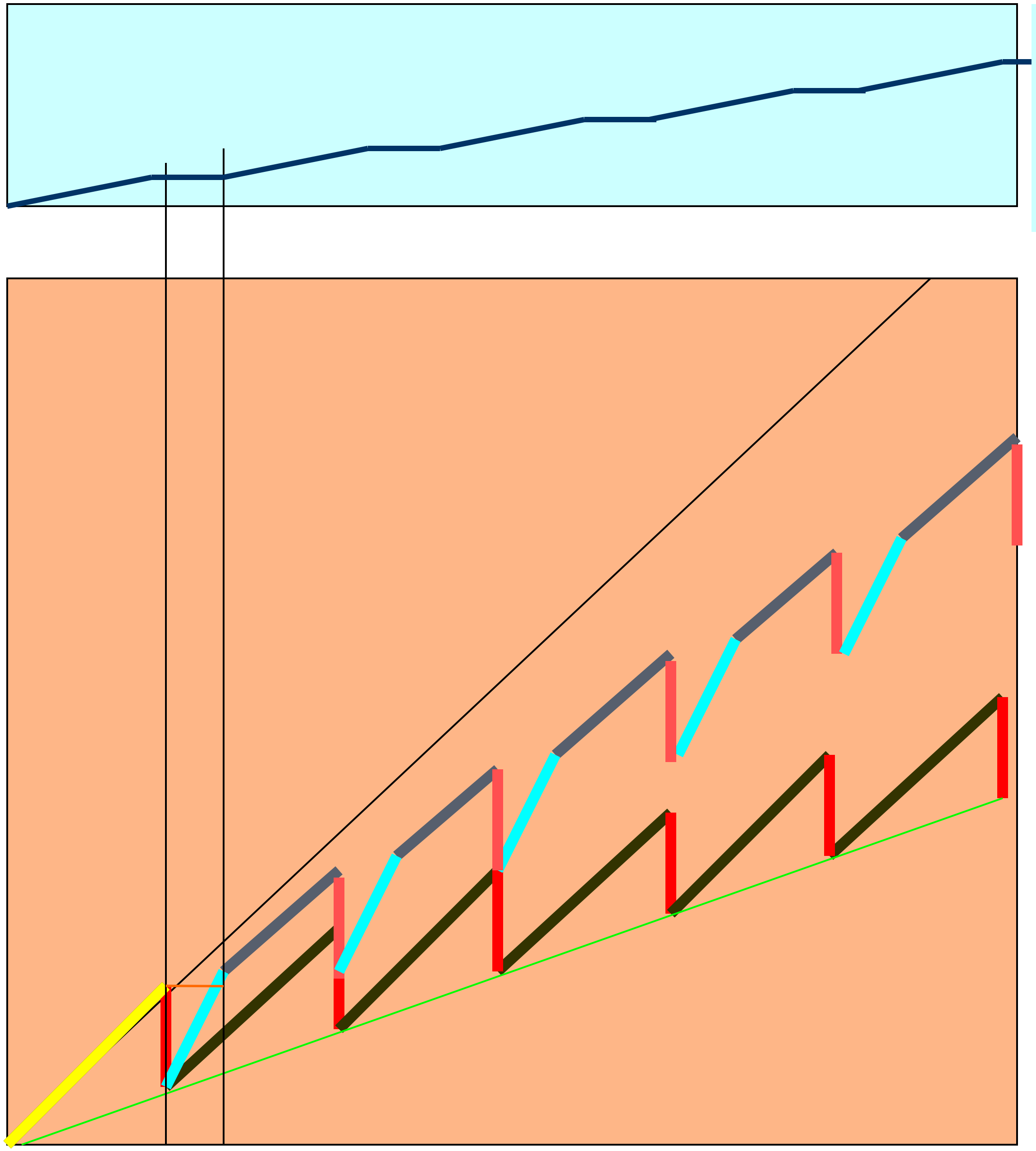




Power consumption is continuous

Normal Checkpoint-Resart method

Progress is slowed down with failures



Power consumption is lower during recovery

Message logging + Object-based virtualization

Progress is faster with failures

Virtualization: Pros, Cons, and Remedies

- We examined the “Pro”s so far.
- Cons and remedies:
  - Memory in ghost layer increases
    - Fuse local regions with compiler support
    - Fetch one ghost layer at a time
    - Hybridize (pthreads/openMP inside objects/DEBs)
  - Less control over scheduling?
    - i.e. too much asynchrony?
    - But can be controlled in various ways by an observant RTS
  - Too radical and new?
    - Well, its working well for the past 10-15 years in multiple applications, via Charm++ and AMPI
  - Too old?
    - What can I say. May be we can invent a new name

New Programming Models

- Simplify parallel programming, improve productivity
- Two broad themes:
- **Frameworks**
  - Encapsulate common data-structure specific code
  - Or domain specific code
  - Avoids duplication/promotes reuse of expensive parallel software
- **Simpler but incomplete languages:**
  - *Restricting* modes of interactions among parallel entities leads to simpler languages
  - Each language may be incomplete but:
    - Addresses important subclasses of algorithms
    - Together with other models, lead to a complete toolkit

Interoperability allows faster evolution of programming models

Evolution doesn’t lead to a single winner species, but to a stable and effective ecosystem.

Similarly, we will get to a collection of viable programming models that co-exists well together.

Compiler Support

- Needed, but in a low-brow way
  - Not for auto-parallelization
- A basic compiler infrastructure
  - Easy to extend
  - Allows code restructuring
  - Supports syntax that improves productivity
  - Basic, well-understood analyses
    - E.g. live-variables analysis for checkpointing
  - **Inserting Control-points to provide knobs to RTS**
- Rose?

Less-technical points

- Where are the youngsters??
  - We have a big problem for the field if young computer scientists are not joining this field
- Need for dialogue:
  - friendly, no-holds-barred, and extensive discussion among the 20 or so leading researchers in the field
  - Feasible now, because most of us are senior (well ☺) researchers, in no need for jockeying, and facing the largest challenge of our times for this field

Summary

- Do away with the notion of processors
  - Adaptive Runtimes, enabled by migratable-objects programming model (aka virtualization)
    - Are necessary at exascale
    - Need to become more intelligent and introspective
    - Help manage accelerators, balance load, tolerate faults,
- Interoperability, concurrent composition become even more important
  - Supported by virtualization
- New programming models and frameworks
  - Create an ecosystem/toolbox of programming paradigms rather than one “super” language
  - Avoid premature standardization