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Characterizing Imbalance in Large-Scale Parallel Programs

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Need for Performance Analysis Tools

- Amount of parallelism in Supercomputers keeps growing
  - Efficient resource usage depends on software performance

Jugene (2008): 65 536 cores

Juqueen (2013): 458 752 cores

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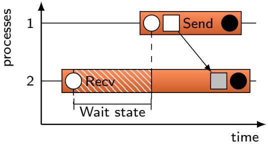
Imbalance limits parallel efficiency

Imbalance leads to wait states at synchronization points



Late-sender wait state

Goal: Locate inefficient parallelism and quantify its impact

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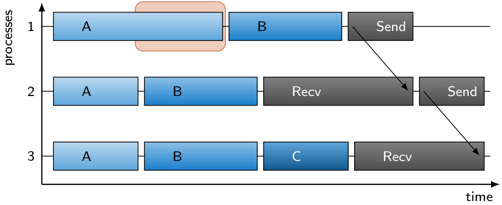
Two novel analysis methods

Root-cause analysis

Critical-path analysis



Determine delays that cause wait states.

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Two novel analysis methods

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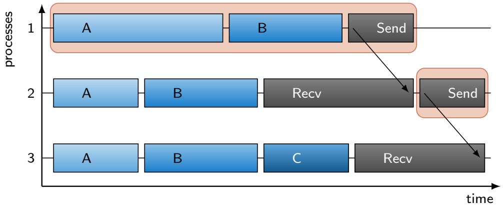
Critical-path analysis



Identify activities that determine program runtime.

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Outline

Parallel Performance Analysis

Root-Cause Analysis

- Concepts
- Case study

Critical-Path Analysis

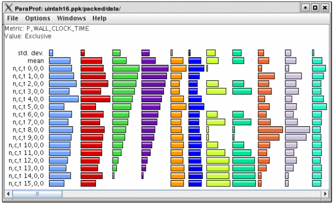
- The critical path
- Critical-path imbalance indicator
- Analysis of MPMD programs

Implementation

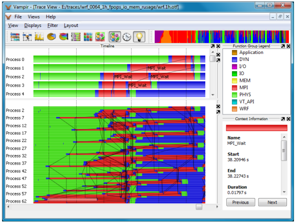
- Parallel trace replay
- Scalability evaluation

Performance analysis tools

- Tools help understand performance, but
  - Profiling provides limited insights
  - Tracing produces too much data to analyze manually



Time profile display in TAU



Event-trace timeline visualization in Vampir

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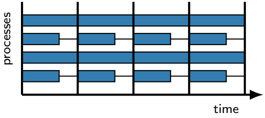
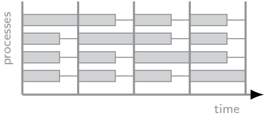
Imbalance analysis pitfalls

- Profilers underestimate impact of imbalance
  - Data aggregation hides dynamic imbalance effects



Static imbalance



Dynamic imbalance

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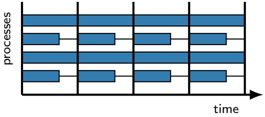
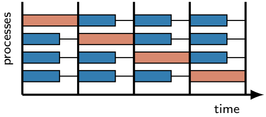


Static imbalance



Dynamic imbalance

- Analysis solution needs to retain performance dynamics

Imbalance analysis pitfalls

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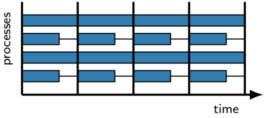
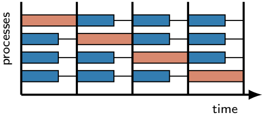


Static imbalance

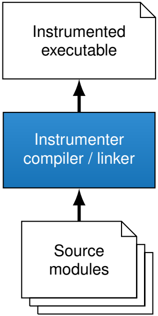


Dynamic imbalance

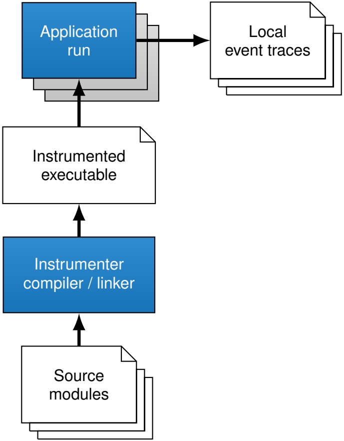
- Analysis solution needs to retain performance dynamics
- Use automatic trace analysis

scalasca

Analysis workflow



Analysis workflow



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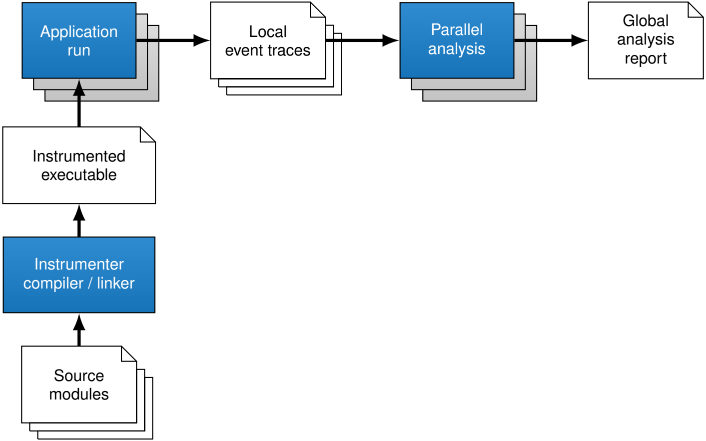

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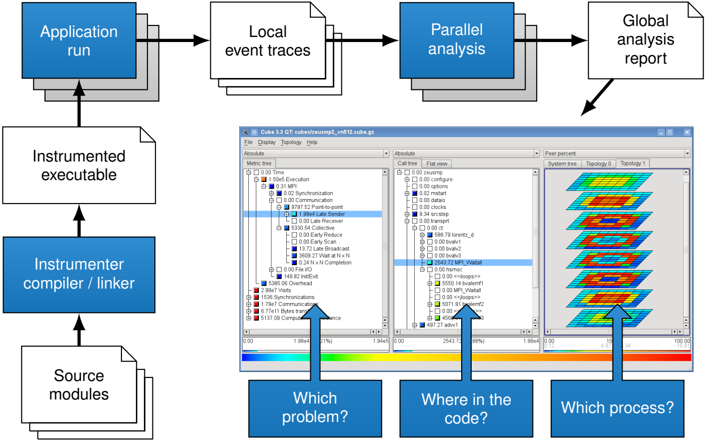

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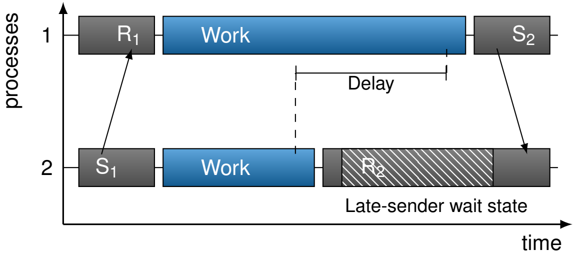
Delay as root cause of wait states

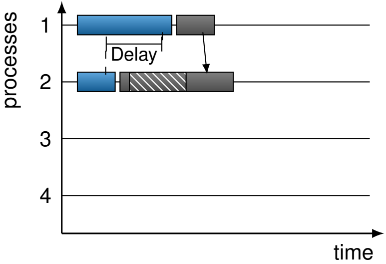
A *delay* is some additional activity on one process that causes a wait state at a synchronization point



Delay on process 1 causes a late-sender wait state on process 2

Wait-state propagation

- Wait states can propagate



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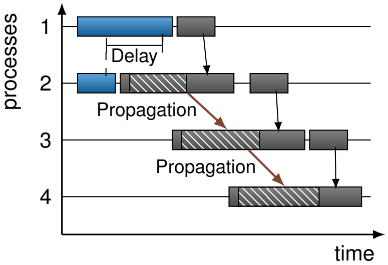
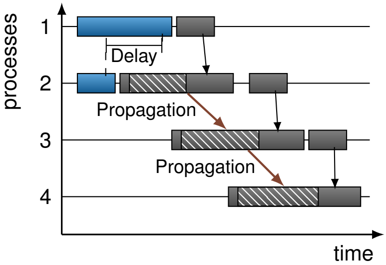


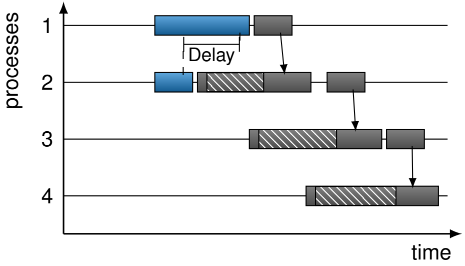
Wait-state propagation

- Wait states can propagate
- Account for propagation in analysis
  - Extended wait-state classification
  - Incorporate long-distance effects in calculation of delay costs



Wait-state classification

Distinguish propagating and terminal wait states



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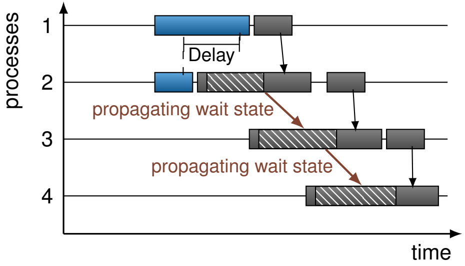

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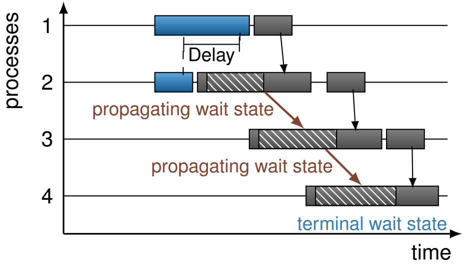
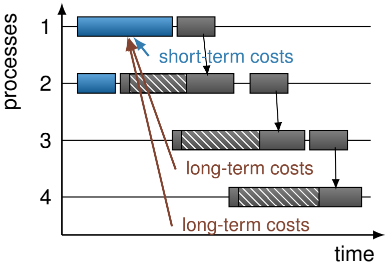


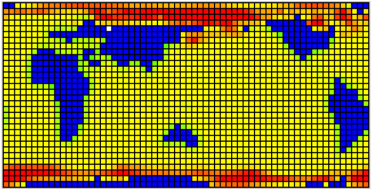
Assigning delay costs

- Delay costs represent amount of wait time caused by a delay
  - Short-term costs represent wait states caused directly
  - Long-term costs represent wait states caused via propagation



Case study: CESM sea ice model

- Analysis of imbalance in CESM sea ice model
- Performance data mapped onto application topology



Distribution of computation time

CICE setup: 2048 processes on BG/P, 1° dipole grid, cartesian grid decomposition

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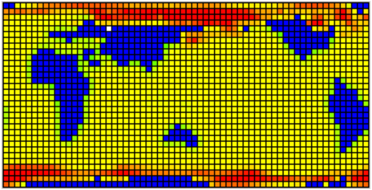

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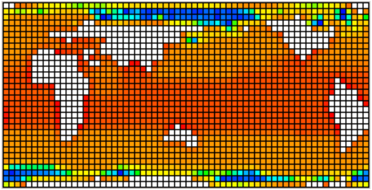
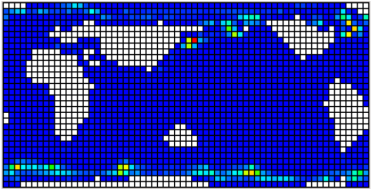


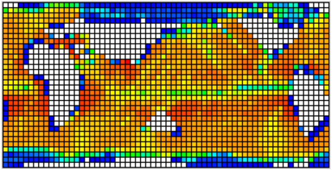
Distribution of late-sender waiting time

CICE setup: 2048 processes on BG/P, 1° dipole grid, cartesian grid decomposition

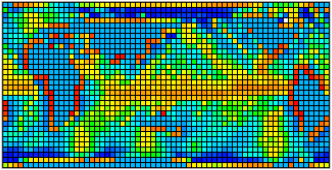
CESM sea ice model: wait-state formation



Distribution of delay costs



Propagating wait states



Terminal wait states

25% Short-term
75% Long-term

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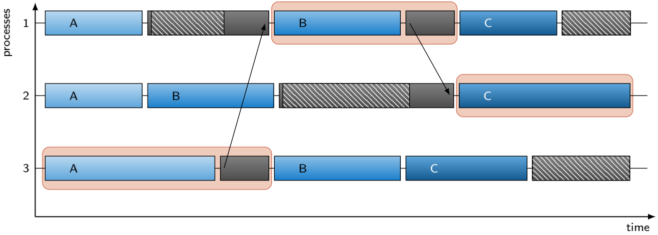
Critical-path analysis

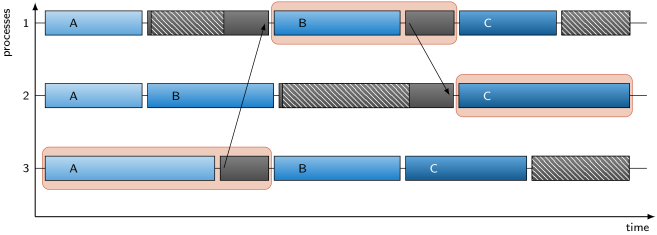
- Use automatic trace analysis to extract the critical path



Critical path in a parallel program (shown in red)

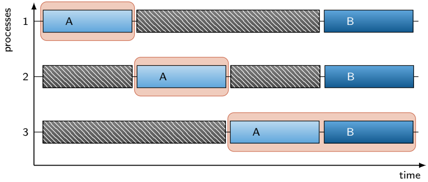
Critical-path analysis

- Use automatic trace analysis to extract the critical path
- Performance indicators show bottlenecks at single glance



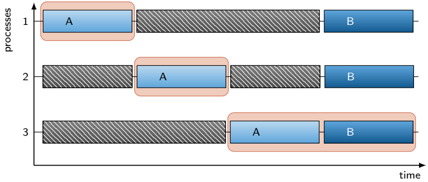
Critical path in a parallel program (shown in red)

Critical-path profile and imbalance



Timeline

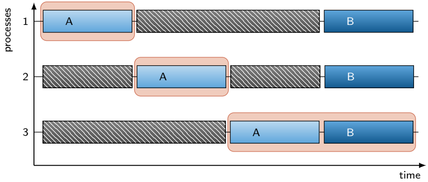
Critical-path profile and imbalance



Timeline

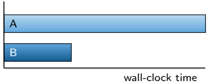
Summary profile

Critical-path profile and imbalance



Timeline

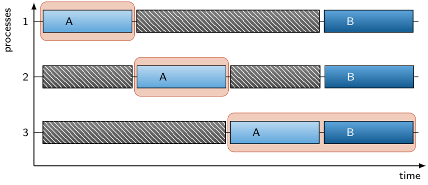
Summary profile



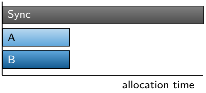
Critical-path profile

- Critical-path profile shows wall-clock time consumption

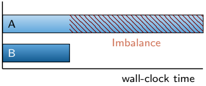
Critical-path profile and imbalance



Timeline



Summary profile

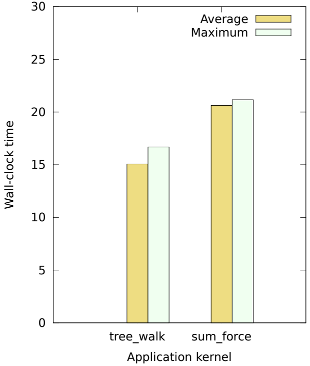


Critical-path profile

- Critical-path profile shows wall-clock time consumption
- Critical imbalance indicator finds inefficient parallelism
  - Imbalance $= T_{critical} - T_{avg}$

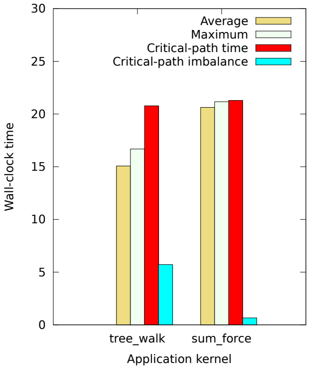
Example: PEPC

- Analysis of plasma-physics code PEPC using 512 processes on Blue Gene/P



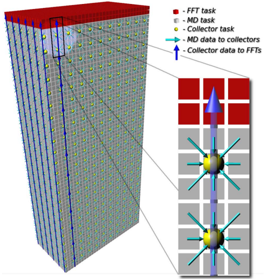
Example: PEPC

- Analysis of plasma-physics code PEPC using 512 processes on Blue Gene/P
- Profile metrics underestimate performance impact of `tree_walk` kernel due to dynamic load imbalance



Analysis of MPMD programs

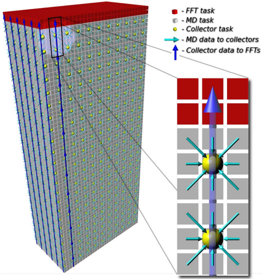
- Processes execute different activities
  - E.g. master-worker



Heterogeneous decomposition in ddcMDD.
Image from Richards et al.: Beyond Homogeneous Decomposition, SC'10

Analysis of MPMD programs

- Processes execute different activities
  - E.g. master-worker
- Complex imbalance analysis issues
  - Not supported by existing tools
  - Imbalance quantification needs to incorporate partition sizes
  - More knobs to tune



Heterogeneous decomposition in ddcMDD.
Image from Richards et al.: Beyond Homogeneous Decomposition, SC'10

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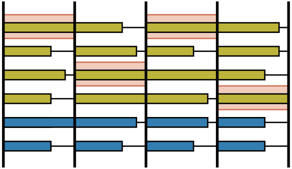
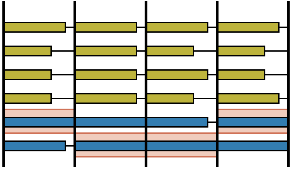
Performance impact indicators

- Denote allocation-time costs of imbalance
  - Map wait time onto critical-path activites with excess time
  - Distinguish intra-partition and inter-partition imbalance costs



High intra-partition costs, low inter-partition costs



Very high inter-partition costs, low intra-partition costs

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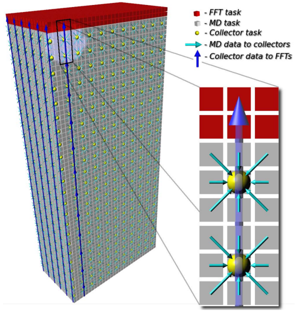
Example: ddcMD

ddcMD molecular dynamics simulation on Blue Gene/P

- *Particle* and *mesh* forces calculated in different partitions



D. Richards et al.: Beyond Homogeneous Decomposition, SC'10

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Example: ddcMD

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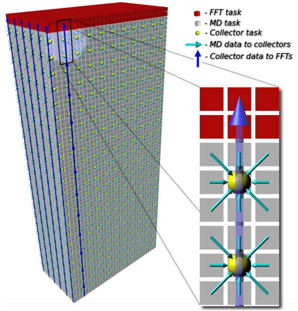
- *Particle* and *mesh* forces calculated in different partitions
- Fixed partition sizes: 3840+256 processes



D. Richards et al.: Beyond Homogeneous Decomposition, SC’10

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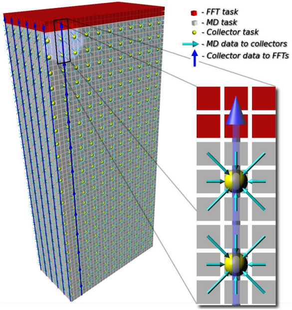
Example: ddcMD

ddcMD molecular dynamics simulation on Blue Gene/P

- *Particle* and *mesh* forces calculated in different partitions
- Fixed partition sizes: 3840+256 processes
- Tune mesh size to adjust load balance



D. Richards et al.: Beyond Homogeneous Decomposition, SC'10

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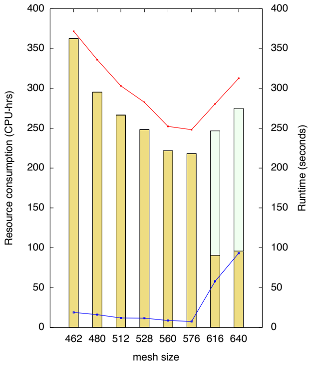
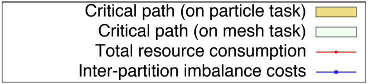
ddcMD: mesh size tuning



- Small mesh size increases workload of particle tasks
- Increasing mesh size shifts critical path to mesh tasks



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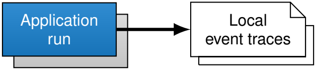
Implementation

- Integrated in Scalasca trace analysis toolset

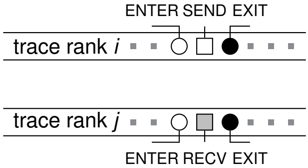
scalasca

- Highly scalable parallel trace analysis
  - So far only for wait-state detection

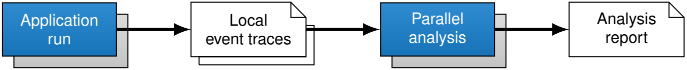
Parallel trace replay



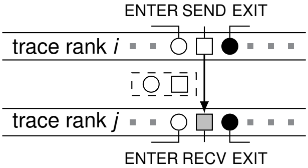
- Application records timestamped communication events
  - One trace file per process



Parallel trace replay

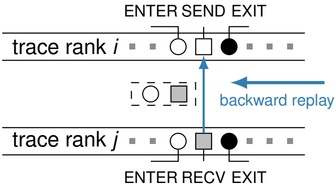


- Application records timestamped communication events
  - One trace file per process
- Analysis processes traverse traces in parallel
  - Exchange information at original synchronization points

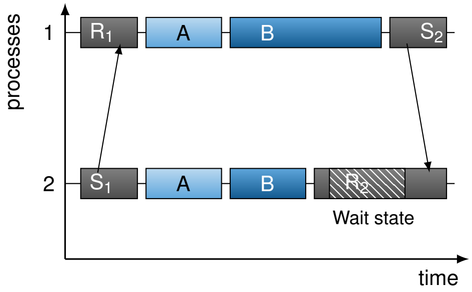


Trace analysis extensions

- Use multiple replay passes
- Backward replay lets data travel from effect to cause



Delay detection via backward replay



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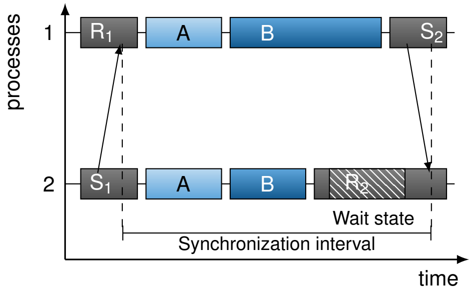
Delay detection via backward replay

1. Identify synchronization interval



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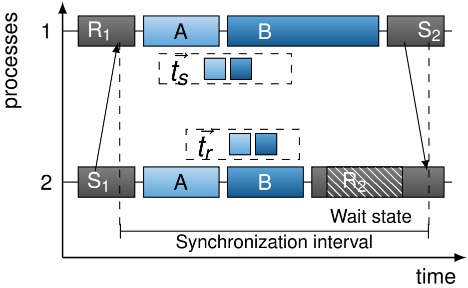
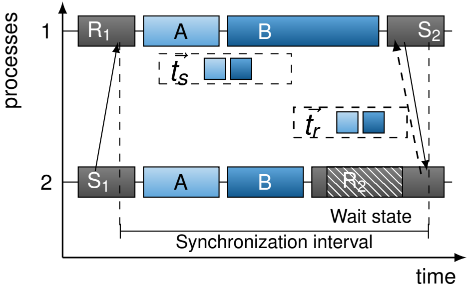
Delay detection via backward replay

1. Identify synchronization interval
2. Determine *time vectors* $\vec{t_s}$ and $\vec{t_r}$



Delay detection via backward replay

1. Identify synchronization interval
2. Determine *time vectors* $\vec{t_s}$ and $\vec{t_r}$
3. Transfer time vector $\vec{t_r}$



Delay detection via backward replay

1. Identify synchronization interval
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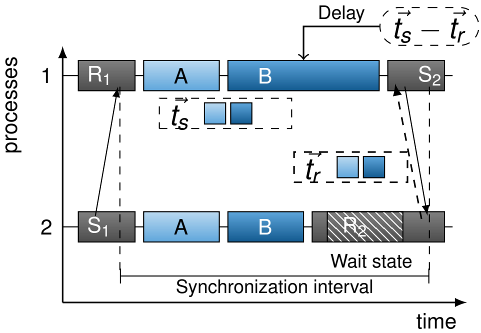
3. Transfer time vector $\vec{t_r}$
4. Locate delay



Delay detection via backward replay

1. Identify synchronization interval
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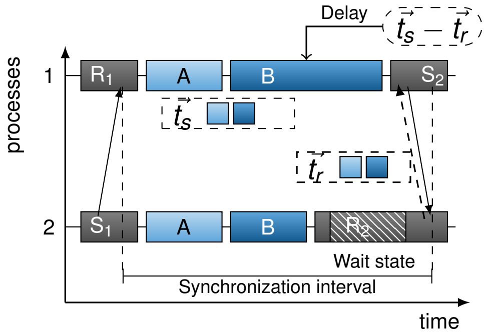
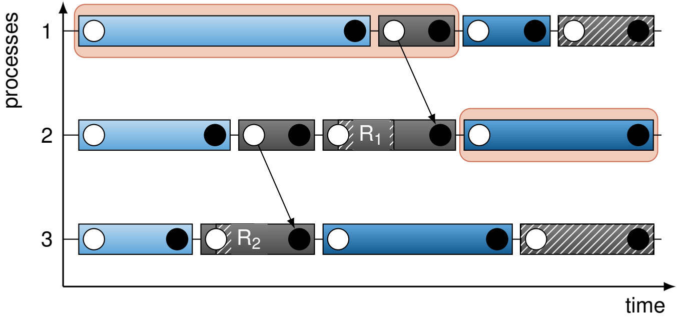
3. Transfer time vector $\vec{t_r}$
4. Locate delay
5. Calculate costs



Critical-path extraction in backward replay



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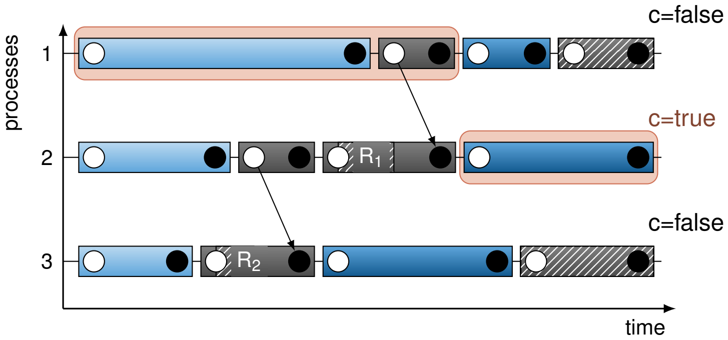

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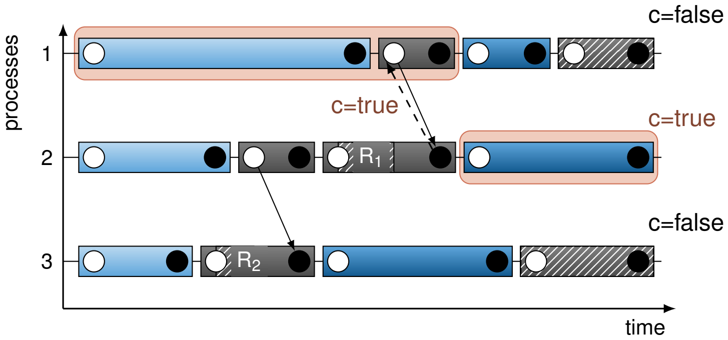

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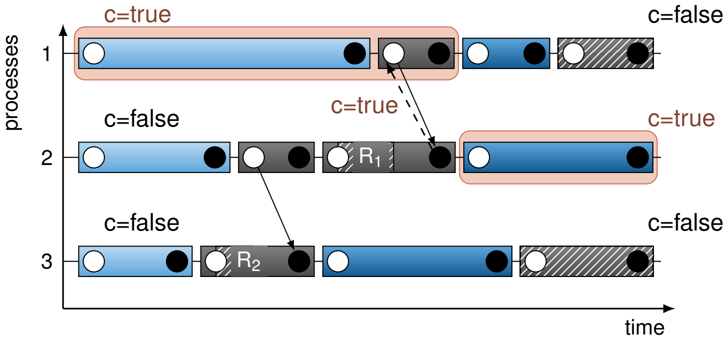
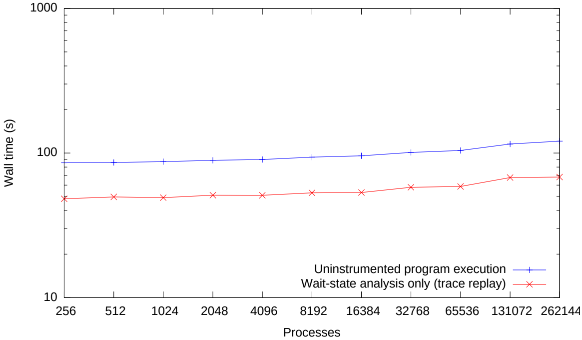
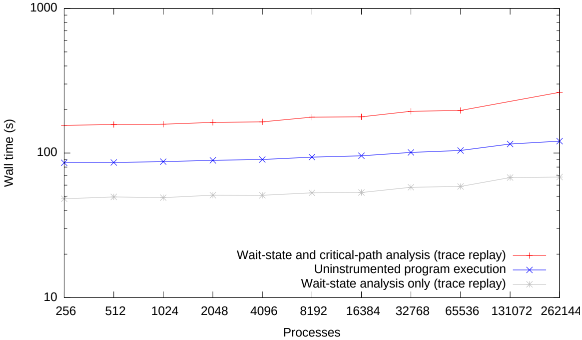


Scalability



Scalability of root-cause and critical-path analysis for the Sweep3D benchmark on Blue Gene/P

Scalability



Scalability of root-cause and critical-path analysis for the Sweep3D benchmark on Blue Gene/P

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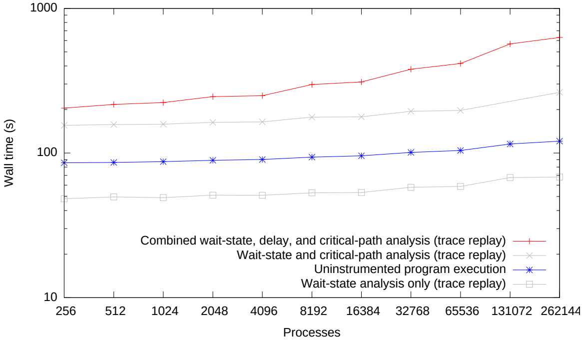


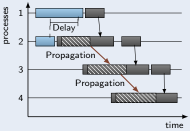
Scalability of root-cause and critical-path analysis for the Sweep3D benchmark on Blue Gene/P

German Research School for Simulation Sciences

Summary

Two novel methods to locate and quantify imbalance

Root-cause analysis



Identifies delays and explains formation of wait states

JÜLICH FORSCHUNGSZENTRUM RWTHAACHEN UNIVERSITY

Summary

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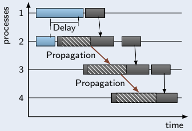

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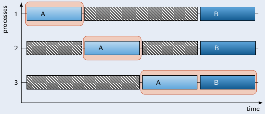

Determines impact of inefficiency on runtime

Summary

Two novel methods to locate and quantify imbalance

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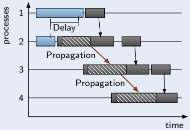

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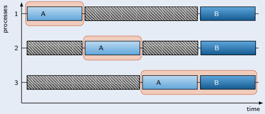
Critical-path analysis



Determines impact of inefficiency on runtime

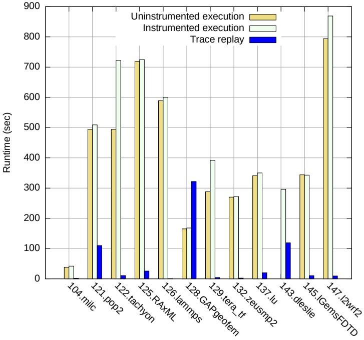
Highly scalable implementation for $\mathcal{O}(100k)$ processes

Thank you

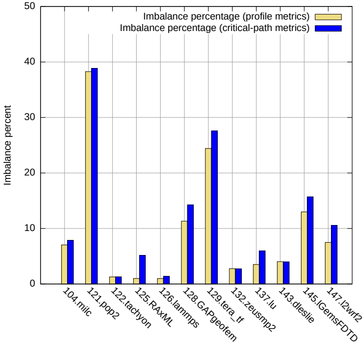
Further reading:

- D. Böhme, B. R. de Supinski, M. Geimer, M. Schulz, and F. Wolf: *Scalable Critical-Path Based Performance Analysis*. IPDPS 2012.
- D. Böhme, M. Geimer, and F. Wolf: *Characterizing Load and Communication Imbalance in Large-Scale Parallel Applications*. IPDPS PhD Forum 2012.
- D. Böhme, M. Geimer, F. Wolf, and L. Arnold: *Identifying the root causes of wait states in large-scale parallel applications*. ICPP 2010. Best paper award.
- D. Böhme, M.-A. Hermanns, M. Geimer, and F. Wolf: *Performance simulation of non-blocking communication in message-passing applications*. PROPER 2009.

SPECMPI case studies



Tracing run-time overhead and trace replay times



Critical-path vs. profile load imbalance metrics