Continuous Runtime Profiling of OpenMP Applications

Karl Fuerlinger, Shirley Moore

{karl,shirley}@cs.utk.edu

INNOVATIVE COMPUTING LABORATORY

COMPUTER SCIENCE DEPARTMENT

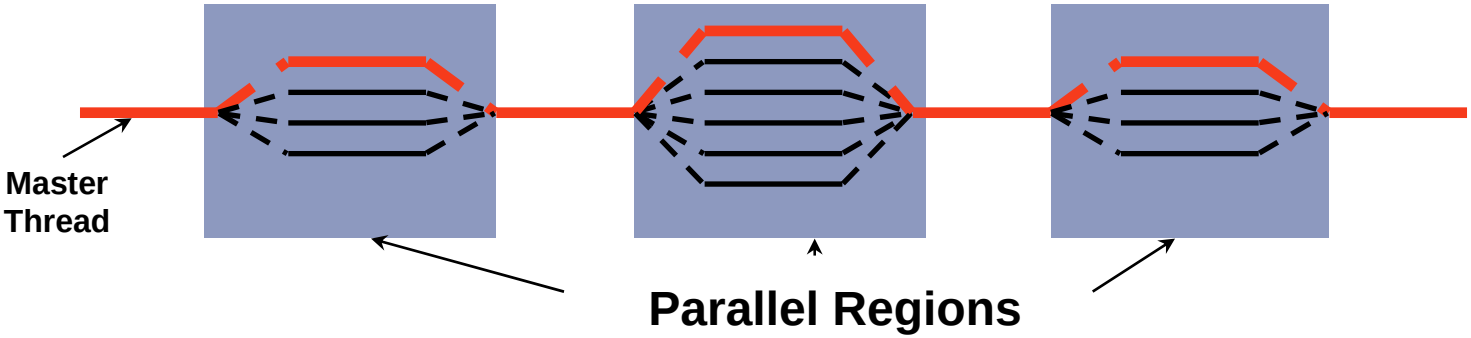
UNIVERSITY OF TENNESSEE

Outline

- Motivation
  - OpenMP and tools support
- ompP: a profiling tool for OpenMP
  - Flat profiles, callgraph profiles, data model
  - Performance properties
  - Overhead classification
- Continuous runtime profiling
  - Adding temporal dimension to profiling-type performance data
  - New performance data views:
    - Overheads, properties over time
    - Performance counter heat-maps
  - Examples from the SPEC OpenMP benchmark suite
- Conclusion and Future work
  - Integration and extension

Motivation (1)

- OpenMP
  - Threads-based and fork/join-oriented programming model
  - Worksharing constructs



- Characteristics
  - Directive based (compiler pragmas, comments)
  - Incremental parallelization approach
  - Well suited for loop-based parallel programming
  - Less well suited for irregular parallelism (*task/taskpool* concepts to be included in upcoming version 3.0 of the OpenMP specification).
  - One of the contending programming paradigms for the “mutlicore era”
  - Traditional roots in the scientific computing community, but:
  - **Microsoft Visual C** and **gcc** now support OpenMP

Motivation (2)

- Tool support for OpenMP is limited
  - No standardized tools interface yet, cf. PMPI interface for MPI
  - Proposal for interface from SUN for version 3.0 of the OpenMP standard
- Vendor specific tools
  - SUN Studio, Intel Thread Profiler, Intel Thread Checker
  - Limited to the particular platform
  - Sampling-based approach
  - Work on system- not user level
- Research tools
  - Most tools use the **POMP** proposal for a performance interface for OpenMP developed by Bernd Mohr et al. (FZ Juelich)
  - Accompanying Source-to-source instrumenter called **Opari**
  - Successful tools for automatic and manual performance analysis have been developed based on this approach
  - TAU (Univ. of Oregon)
  - KOJAK (Univ. of Tennessee and FZ Juelich)
  - **ompP**: Pure profiling tool with text-based output

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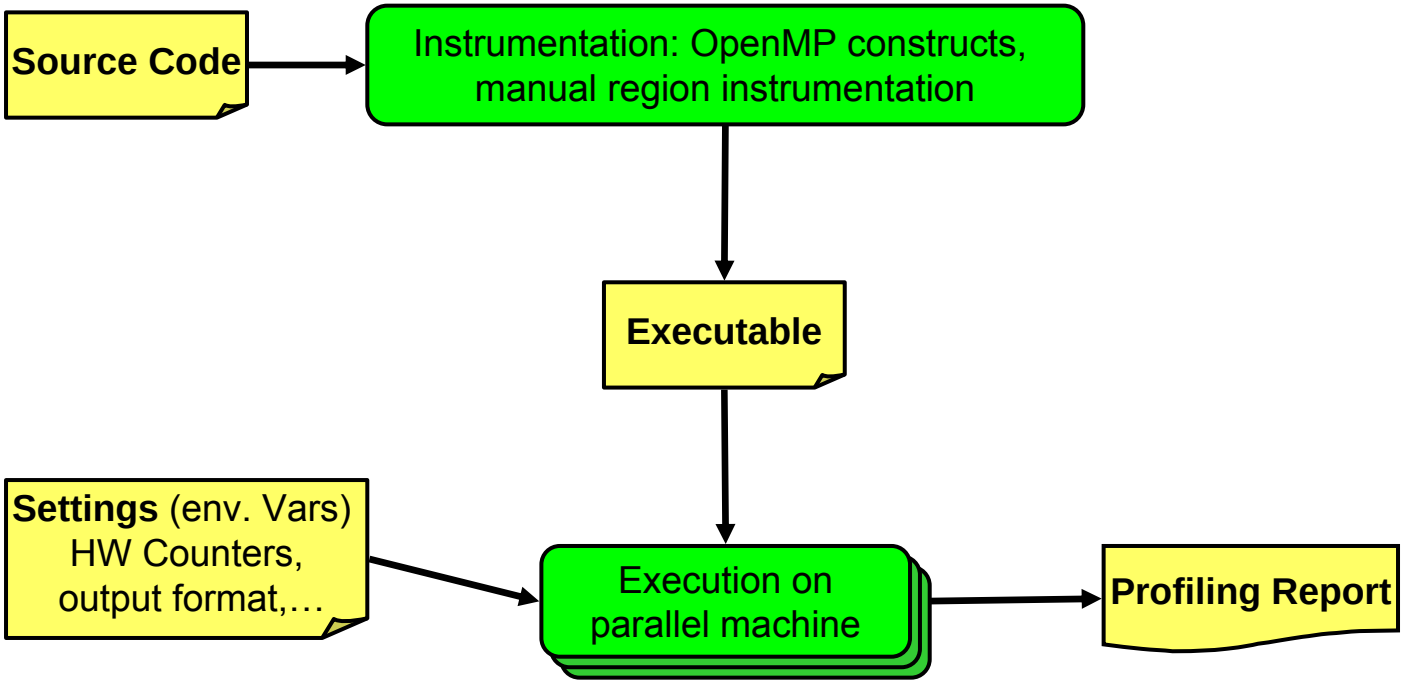
ompP (1)

- ompP is a profiling tool for OpenMP
  - Available with user guide and manual under GPL license from http://www.ompp-tool.com
  - Works with all Unix-like OS and OpenMP compiler combinations
  - Tested and supported: Linux, Solaris, AIX and Intel, Pathscale, PGI, IBM, gcc compilers



ompP (2)

- Characteristics:
  - Target application can be written in **FORTRAN** or **C/C++**
  - ompP is implemented as a **static library** linked to the target application
  - Source-code instrumentation with **Opari**
  - Simple usage with wrapper script, e.g., **`kinst-ompp icc -o test test.c`**
  - Setting options as environment variables, e.g., **`export OMPP_OUTFORMAT=csv`**
  - Reports execution **times and counts** for various OpenMP constructs
  - Data is presented in terms of the **user model** of execution, not the system model
  - Supports **HW counters** using **PAPI**
  - **ASCII based profiling report** is delivered at program end

ompP (3)

- Advanced productivity features
  - **Evaluators**
    - Compute expressions involving HW counters directly
    - Ex: **`OMPP_EVAL1=1-L2_MISSES/L2_REFERENCES`**
  - **Mid-run dumping** of the profiling report is supported
    - Useful for long-running applications
  - **Overhead** Analysis
    - Four well defined overhead categories of parallel execution
    - Analysis for individual parallel region and whole program
  - **Scalability** Analysis
    - Analyze overheads for increasing thread counts
  - **Performance Properties**
    - Detect common inefficiency situations
  - **Continuous runtime profiling**
    - Profiling-over-time adds temporal dimension

ompP's Profiling Report

- General Information
  - Date, time, duration of the run, number of threads, used hardware counters,…
- Region Overview
  - Number of regions and their source-code locations
- Flat Region Profile
  - Inclusive times, counts, hardware counter data
- Callgraph (-tree)
- Callgraph Profiles
  - Inclusive and exclusive data
- Overhead Analysis Report
  - Four overhead categories, per-parallel region breakdown, absolute times and percentages
- Performance Property Detection Report
  - Points out common inefficiency situations

Flat Region Profile (1)

- Example:

```
R00002 main.c (34-37) (default) CRITICAL
 TID      execT      execC      bodyT     enterT      exitT   PAPI_TOT_INS
   0       3.00          1       1.00       2.00       0.00           1595
   1       1.00          1       1.00       0.00       0.00           6347
   2       2.00          1       1.00       1.00       0.00           1595
   3       4.00          1       1.00       3.00       0.00           1595
 SUM      10.01          4       4.00       6.00       0.00          11132
```

- Components:
  - Region Number
  - Source code location and region type
  - Timing data and execution counts, **depending on the particular construct**
  - One line per thread, last line sums over all threads
  - Hardware counter data (if PAPI is available and HW counters are selected)

Flat Region Profile (2)

- Times and counts reported by ompP for various OpenMP constructs

	main		*enter*		*body*					*barr*	*exit*	
construct	execT	execC	enterT	startupT	bodyT	sectionT	sectionC	singleT	singleC	exitBarT	exitT	shutdwnT
MASTER	•	•										
ATOMIC	•	•										
BARRIER	•	•										
FLUSH	•	•										
USER REGION	•	•										
CRITICAL	•	•	•		•						•	
LOCK	•	•	•		•						•	
LOOP	•	•			•					•		
WORKSHARE	•	•			•					•		
SECTIONS	•	•				•	•			•		
SINGLE	•	•						•	•	•		
PARALLEL	•	•		•	•					•		•
PARALLEL LOOP	•	•		•	•					•		•
PARALLEL SECTIONS	•	•		•		•	•			•		•
PARALLEL WORKSHARE	•	•		•	•					•		•

____T: time

____C: count

Main =
enter +
body +
barr +
exit

Overhead Analysis (1)

- Certain timing categories reported by ompP can be classified as overheads:
  - Example: **`exitBarT`**: Time wasted by threads idling at the exit barrier of work-sharing constructs. Reason is most likely an **imbalanced** amount of work
- Four overhead categories are defined in ompP:
  - **Imbalance**: waiting time incurred due to an imbalanced amount of work in a worksharing or parallel region
  - **Synchronization**: overhead that arises due to threads having to synchronize their activity, e.g. **`barrier`** call
  - **Limited Parallelism**: idle threads due not enough parallelism being exposed by the program
  - **Thread management**: overhead for the creation and destruction of threads, and for signaling critical sections, locks as available

Overhead Analysis (2)

	main		*enter*		*body*					*barr*	*exit*	
construct	execT	execC	enterT	startupT	bodyT	sectionT	sectionC	singleT	singleC	exitBarT	exitT	shutdwnT
MASTER	•	•										
ATOMIC	•(S)	•										
BARRIER	•(S)	•										
FLUSH	•(S)	•										
USER REGION	•	•										
CRITICAL	•	•	•(S)		•						•(M)	
LOCK	•	•	•(S)		•						•(M)	
LOOP	•	•			•					•(I)		
WORKSHARE	•	•			•					•(I)		
SECTIONS	•	•				•	•			•(I/L)		
SINGLE	•	•						•	•	•(L)		
PARALLEL	•	•		•(M)	•					•(I)		•(M)
PARALLEL LOOP	•	•		•(M)	•					•(I)		•(M)
PARALLEL SECTIONS	•	•		•(M)		•	•			•(I/L)		•(M)
PARALLEL WORKSHARE	•	•		•(M)	•					•(I)		•(M)

S: Synchronization overhead

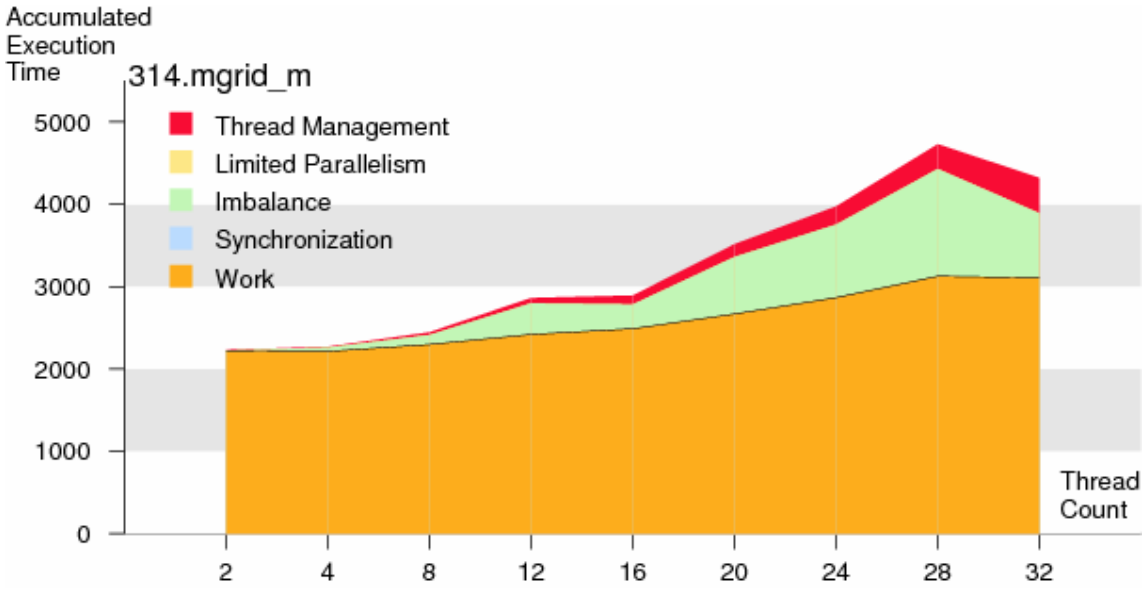
I: Imbalance overhead

M: Thread management overhead

L: Limited Parallelism overhead

OpenMP Scalability Analysis

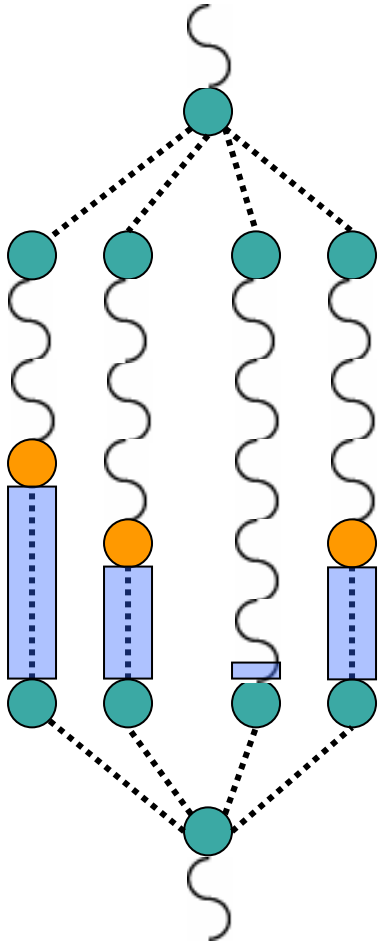
- Methodology
  - Classify execution time into “Work” and four overhead categories: “Thread Management”, “Limited Parallelism”, “Imbalance”, “Synchronization”
  - Analyze how overheads behave for increasing thread counts
  - Graphs show accumulated runtime over all threads for fixed workload (strong scaling)
  - Application example: 314.mgrid_m from the SPEC OpenMP benchmark suite



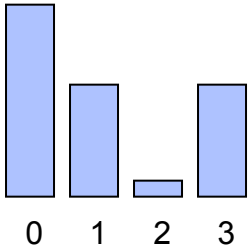
- Scaling from 2 to 32 processors on an SGI Altix machine
- Markedly smaller load imbalance for thread counts of 32 and 16. Only three parallel loops show this behavior
- In all three cases, the iteration count is always a power of two (2 to 256), hence thread counts which are not a power of two exhibit larer load imbalance

Performance Properties (1)

- Other way to look at overheads
  - Example: parallel region with 4 threads, load is imbalanced



exitBarT[i] time that thread i spends in the “exit barrier”, quantifies load imbalance




```
Property ImabalanceInParallelRegion
{
let
   imbal=exitBarT[0]+…+exitBarT[N-1];

Condition: (region.type)==PARALLEL && (imbal>0.0);

Severity: imbal/(total runtime * number of threads);

}
```

ASL formalism to specify properties

Performance Properties (2)

- Detection of common inefficiency situations:
  - Severity is fraction of total runtime lost due to the inefficiency
  - Supported performance properties:
    - WaitAtBarrier
    - ImbalanceInParallelRegion
    - ImbalanceInParallelLoop, -Workshare ,-Sections
    - ImbalanceDueToNotEnoughSections
    - ImbalanceDueToUnevenSectionDistribution
    - CriticalSectionContention, LockContention
    - FrequentAtomic
    - InsufficienWorkInParallelLoop
    - UnparallelizedInMasterRegion, -SingleRegion

```
------------------------------------------------------------------------
----     ompP Performance Properties Report    ----------------------
------------------------------------------------------------------------

PROPERTY 'ImbalanceInParallelRegion' holds for
     'PARALLEL zaxpy.F (48-81)', with a severity of 0.041476

PROPERTY 'ImbalanceInParallelLoop' holds for
     'LOOP zaxpy.F (55-59)', with a severity of 0.035408
...
```

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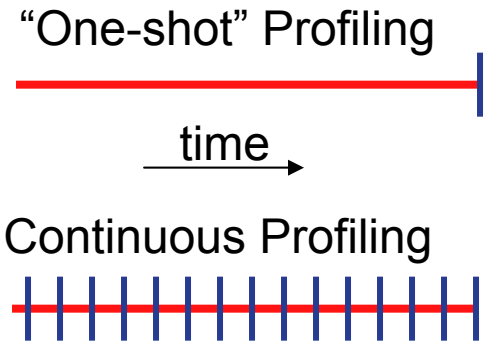
Continuous Runtime Profiling

- Profiling vs. Tracing
  - Profiling:
    - Low overhead, smaller amounts of data
    - Easier to comprehend, textual interpretation possible
  - Tracing:
    - Large quantities of data, hard to comprehend manually
    - Can explain temporal phenomena, causal relationships of events are preserved
- Continuous runtime profiling: try to combine advantages of profiling and tracing
  - Add a temporal dimension to profiling-type performance data
  - See what happens during the execution without capturing full traces
  - Manual interpretation becomes harder since a new dimension is added to the performance data
- Implementation:
  - Capture and dump profiling reports not only at the end of the execution but several times while the application executes
  - Analyze how profiling reports change over time

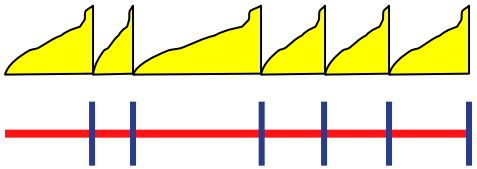


Continuous Runtime Profiling

- Triggers for capturing profiles:
  - **Timer-based, fixed**: capture profiles in regular, uniform intervals: predictable storage requirements (depends only on duration of program run, size of dataset).

  - **Timer-based, adaptive**: Adapt the capture rate to the behavior of the application: dump often if application behavior changes, decrease rate if application behavior stays the same

  - **Overflow-based**: Dump a profile if a hardware counter overflows. Interesting for floating point intensive application



  - **User-added:** Expose API for dumping profiles to the user aligned to outer loop iterations or phase boundaries

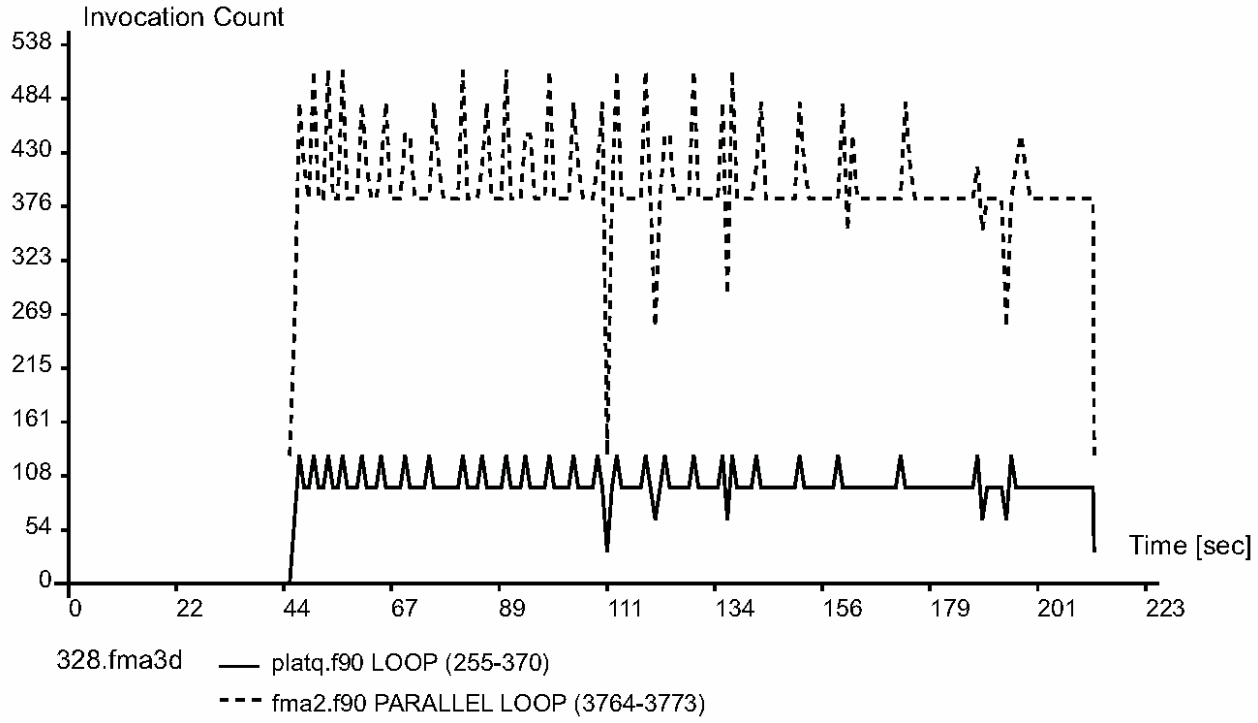
Continuous Runtime Profiling

- Trigger currently implemented in ompP:
  - Capture profiles in regular intervals (selectable, 1 sec used in the experiments)
  - Timer signal is registered and delivered to profiler
  - Profiling data up to capture point stored to memory buffer
  - Dumped as individual profiling reports at the end of program execution
  - Perl scripts to analyze reports and generate graphs

- Experiments
  - SPEC OpenMP benchmark suite
    - Medium variant, 11 applications
  - 32 CPU SGI Altix machine
    - Itanium-2 processors with 1.6 GHz and 6 MB L3 cache
    - Used in batch mode

Continous Profiling: Data Views (1)

- 1. Region invocations over Time
  - See which OpenMP region was executed how often and when during the execution of the application
  - Either for a particular thread or summed over all threads
  - Two most time-consuming regions of application 328.fma3d:

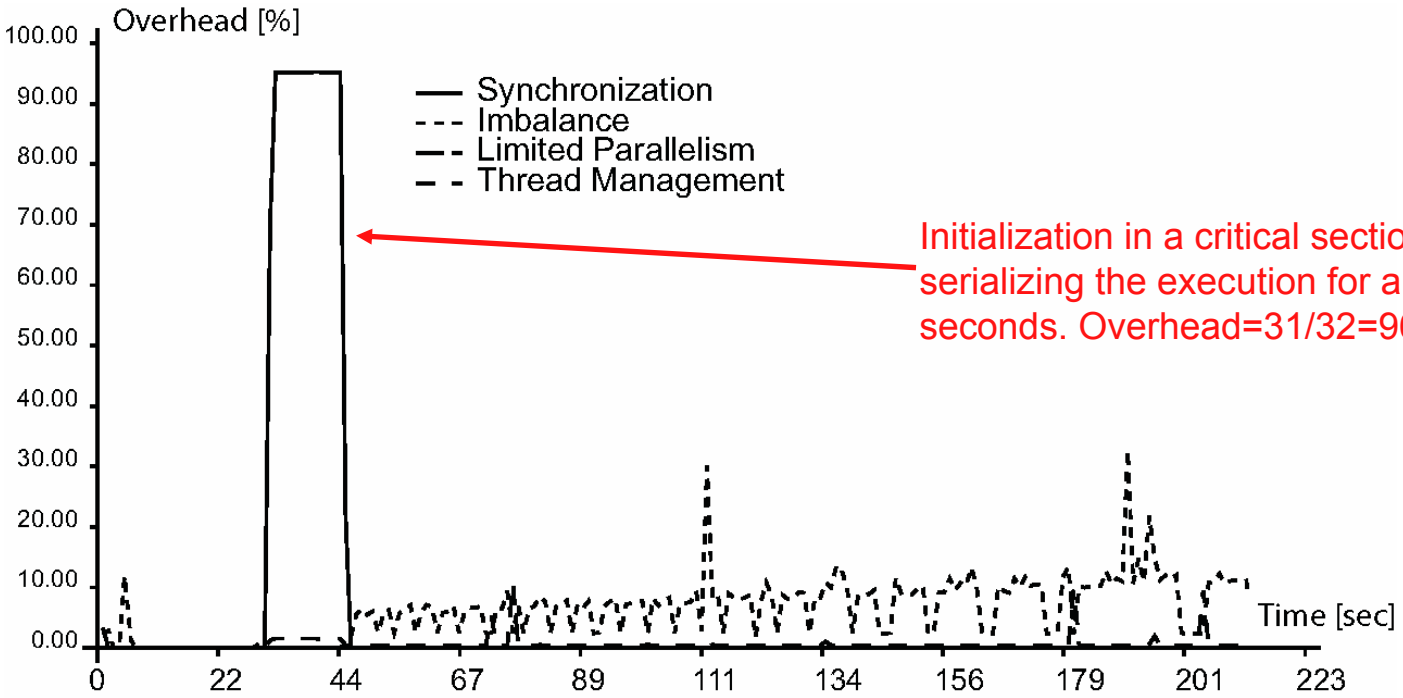


- 2: Region execution time over time
  - same as invocations but use time instead of execution count

Continuous Profiling: Data Views (2)

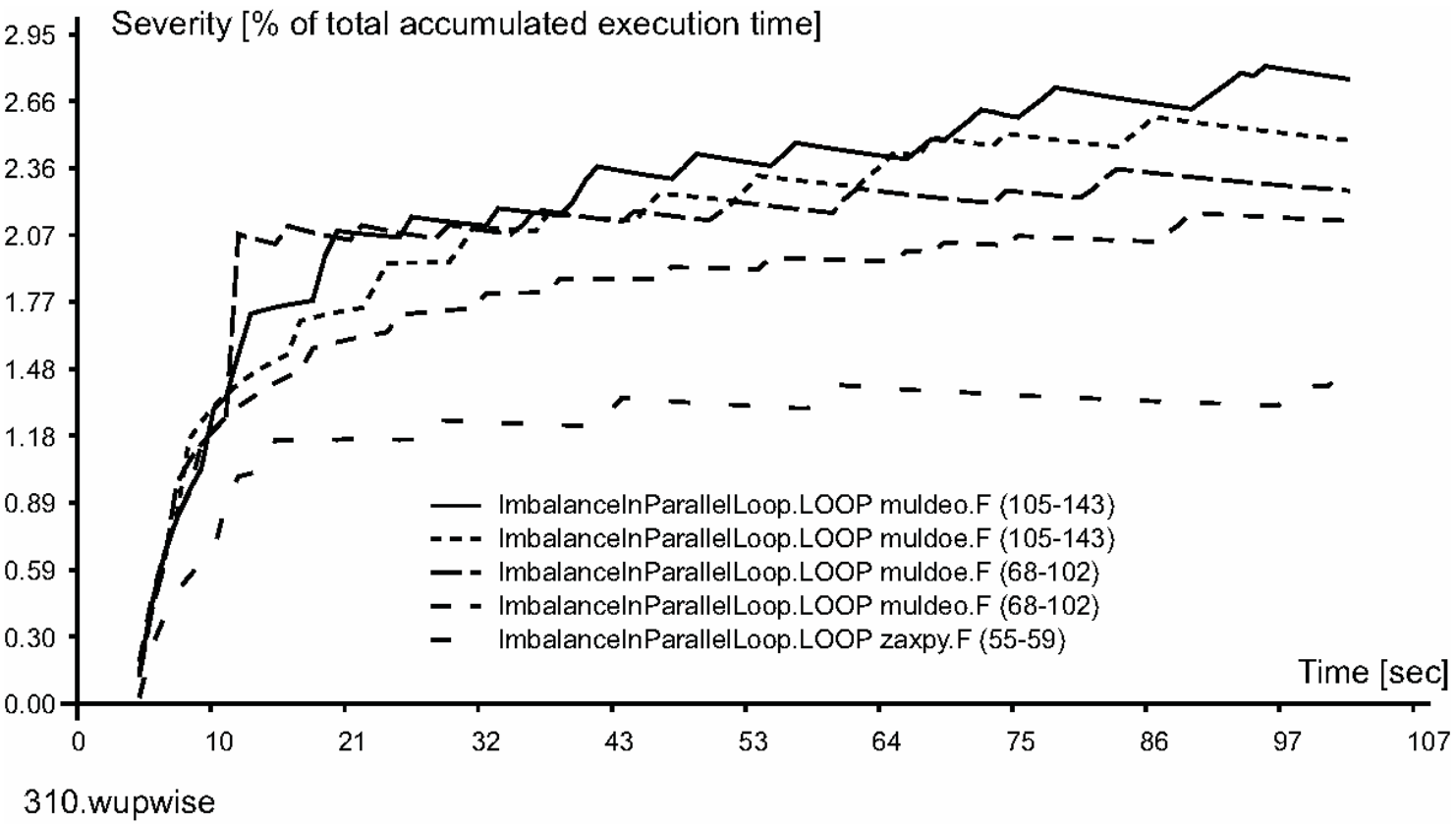
- 3. Overheads over time
  - See how overheads develop over the application run
  - How is each Δt (1sec) spent for work or for one of the overhead classes
  - Either for whole program or for a specific parallel region
  - Total incurred overhead=integral under this function

Application: 328.fma3d_m



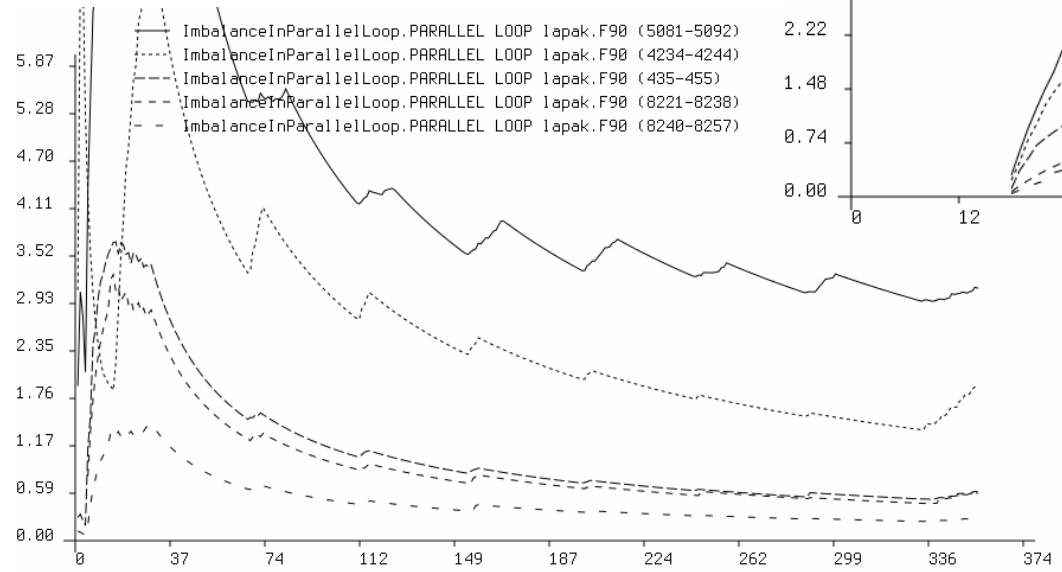
Continuous Profiling: Data Views (3)

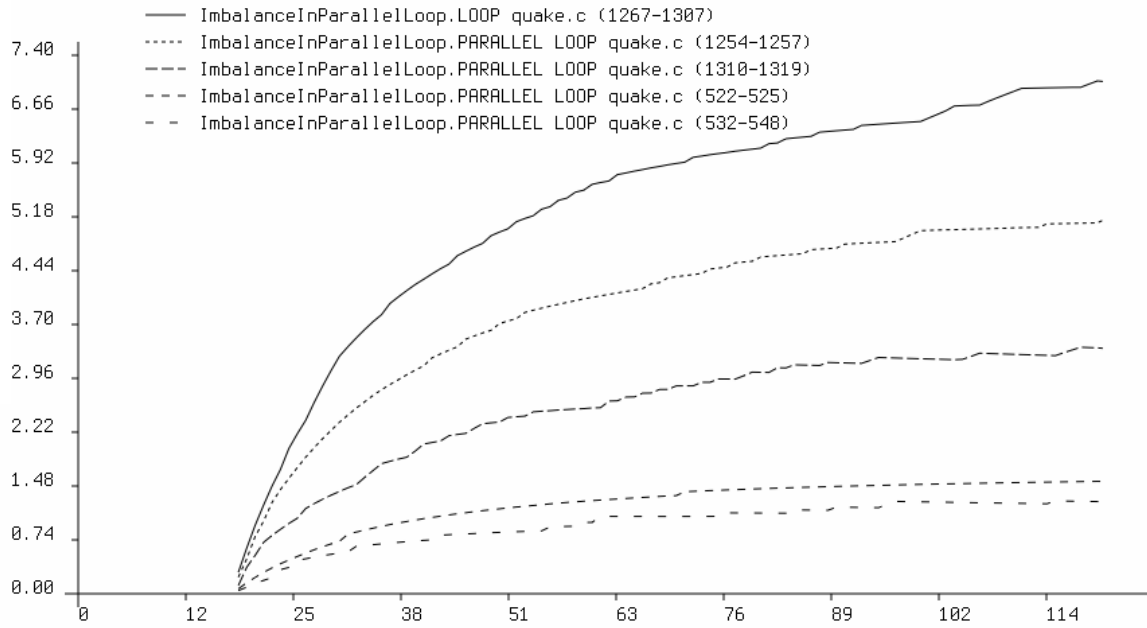
- 4. Performance Properties over time
  - Severity: negative impact on performance up to the capture point: percentage of CPU time lost due to inefficiency situation



Continuous Profiling: Data Views (4)

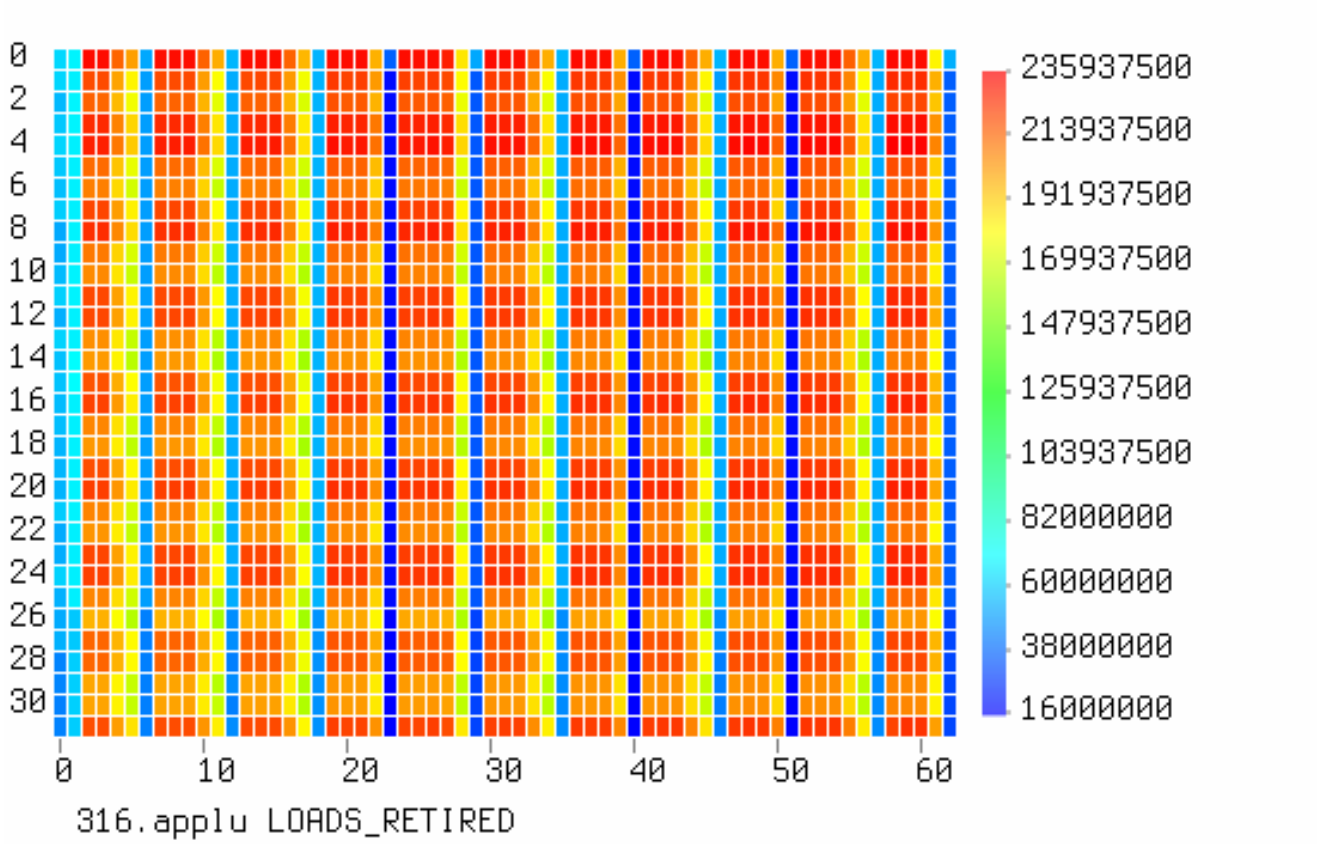
- 4. Performance Properties over time (contd.)
  - 318.galgel
  - 324.equake





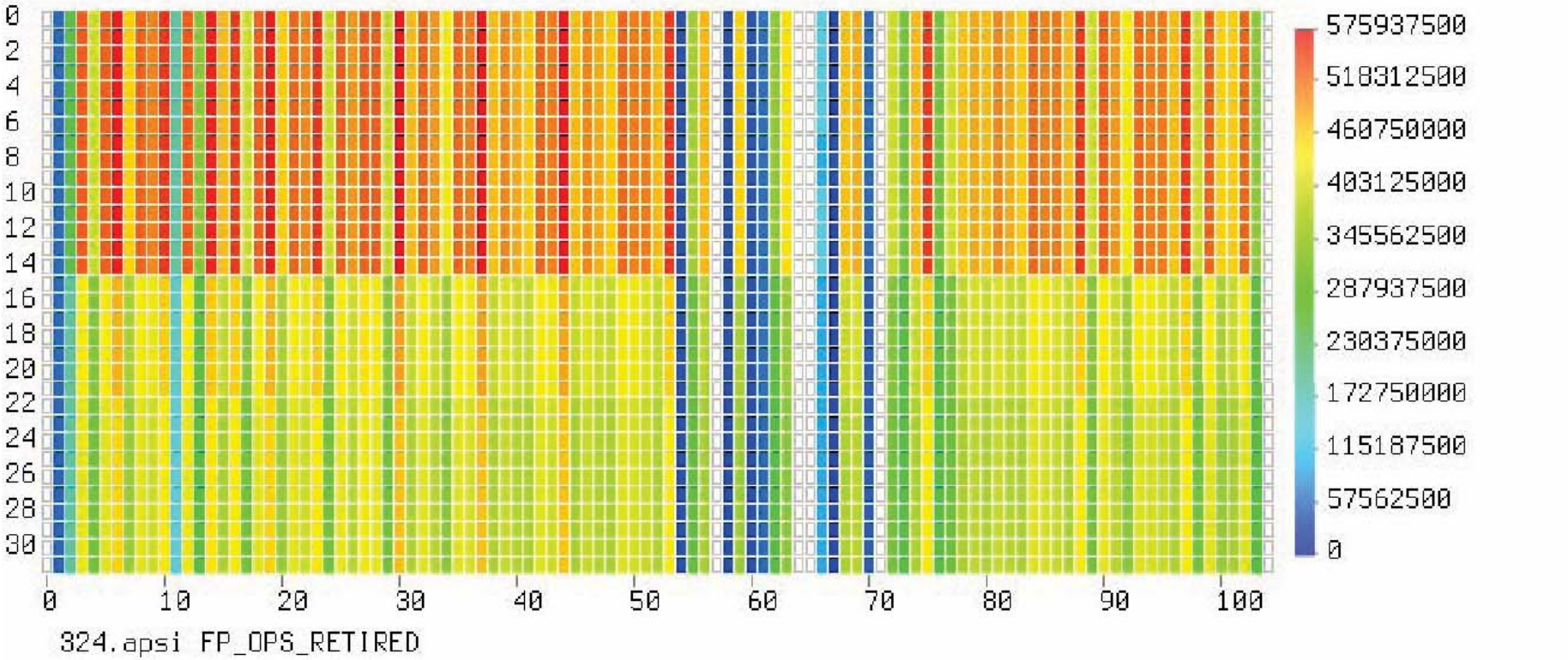
Continuous Profiling

- Performance counter heatmaps
  - x-axis: Time, y-axis: Thread-ID
  - Color: number of hardware counter events observed during sampling period
  - Application “**applu**”, medium-sized variant, counter: **LOADS_RETIRED**
  - Visible phenomena: iterative behavior, thread grouping (pairs)



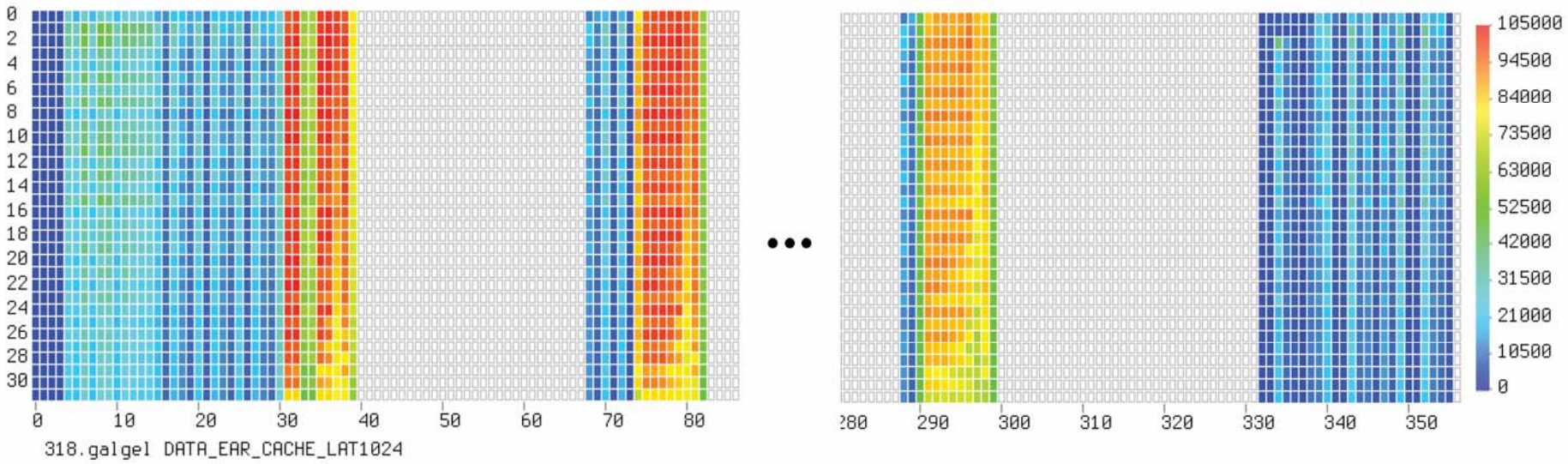
Continuous Profiling

- Performance counter heatmaps (contd.)
  - Application “**apsi**”, medium-sized variant, counter: **FP_OPS_RETIRED**
  - Visible phenomena: difference in thread behavior. Maybe related to placement of threads on processors



Continuous Profiling

- Performance counter heatmaps contd.
  - Application “**galgel**”, medium-sized variant, counter: **DATA_EAR_CACHE_LAT1024**
  - Visible phenomena: iterative behavior, stagger-pattern
  - Middle of the timeline cut-out



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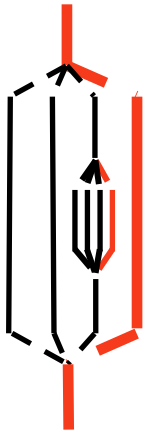
Conclusion

- Continuous runtime profiling
  - Add temporal dimension to profiling type performance data
  - Good balance between simplicity of profiling and insight of tracing
- Phenomena that can be identified
  - Temporal location of contention for resources
  - When constructs get executed
  - Grouping of threads
  - Iterative behavior

Future Work

- Integration with MPI profiler mpiP
  - Profiling for mixed-parallel codes
  - Different models of combined usage of OpenMP and MPI
  - MPI-time as communication overhead in ompP's overhead analysis
- Support for nested OpenMP parallelism
  - Increasing interest in this model due to hierarchical organization of processing elelements
- Further investigation of continuous profiling
  - Other triggers (API, hardware-counter based)
  - Analyze and explain visible patterns, starting from application kernels.
- http://www.ompp-tool.com



Thank you for your attention!

- Backup Slides

Overhead Analysis Report

```
---------------------------------------------------------------------
----     ompP Overhead Analysis Report    ---------------------------
---------------------------------------------------------------------
Total runtime (wallclock)   : 172.64 sec [32 threads]
Number of parallel regions  : 12
Parallel coverage           : 134.83 sec (78.10%)

Parallel regions sorted by wallclock time:
          Type                                Location      Wallclock (%)
R00011  PARALL                    mgrid.F (360-384)      55.75 (32.29)
R00019  PARALL                    mgrid.F (403-427)      23.02 (13.34)
R00009  PARALL                    mgrid.F (204-217)      11.94 ( 6.92)
...
                                                  SUM     134.83 (78.10)

Overheads wrt. each individual parallel region:
          Total        Ovhds (%)  =   Synch  (%)  +  Imbal   (%)  +   Limpar (%)   +    Mgmt (%)
R00011  1783.95   337.26 (18.91)    0.00 ( 0.00)  305.75 (17.14)    0.00 ( 0.00)   31.51 ( 1.77)
R00019   736.80   129.95 (17.64)    0.00 ( 0.00)  104.28 (14.15)    0.00 ( 0.00)   25.66 ( 3.48)
R00009   382.15   183.14 (47.92)    0.00 ( 0.00)   96.47 (25.24)    0.00 ( 0.00)   86.67 (22.68)
R00015   276.11    68.85 (24.94)    0.00 ( 0.00)   51.15 (18.52)    0.00 ( 0.00)   17.70 ( 6.41)
...

Overheads wrt. whole program:
          Total        Ovhds (%)  =   Synch  (%)  +  Imbal   (%)  +   Limpar (%)   +    Mgmt (%)
R00011  1783.95   337.26 ( 6.10)    0.00 ( 0.00)  305.75 ( 5.53)    0.00 ( 0.00)   31.51 ( 0.57)
R00009   382.15   183.14 ( 3.32)    0.00 ( 0.00)   96.47 ( 1.75)    0.00 ( 0.00)   86.67 ( 1.57)
R00005   264.16   164.90 ( 2.98)    0.00 ( 0.00)   63.92 ( 1.16)    0.00 ( 0.00)  100.98 ( 1.83)
R00007   230.63   151.91 ( 2.75)    0.00 ( 0.00)   68.58 ( 1.24)    0.00 ( 0.00)   83.33 ( 1.51)
...
   SUM  4314.62  1277.89 (23.13)    0.00 ( 0.00)  872.92 (15.80)    0.00 ( 0.00)  404.97 ( 7.33)
```

Number of threads, parallel regions, parallel coverage

Wallclock time x number of threads

Overhead percentages wrt. this particular parallel region

Overhead percentages wrt. whole program