Mitglied der Helmholtz-Gemeinschaft

Application Performance Analysis

– Tools and Techniques –

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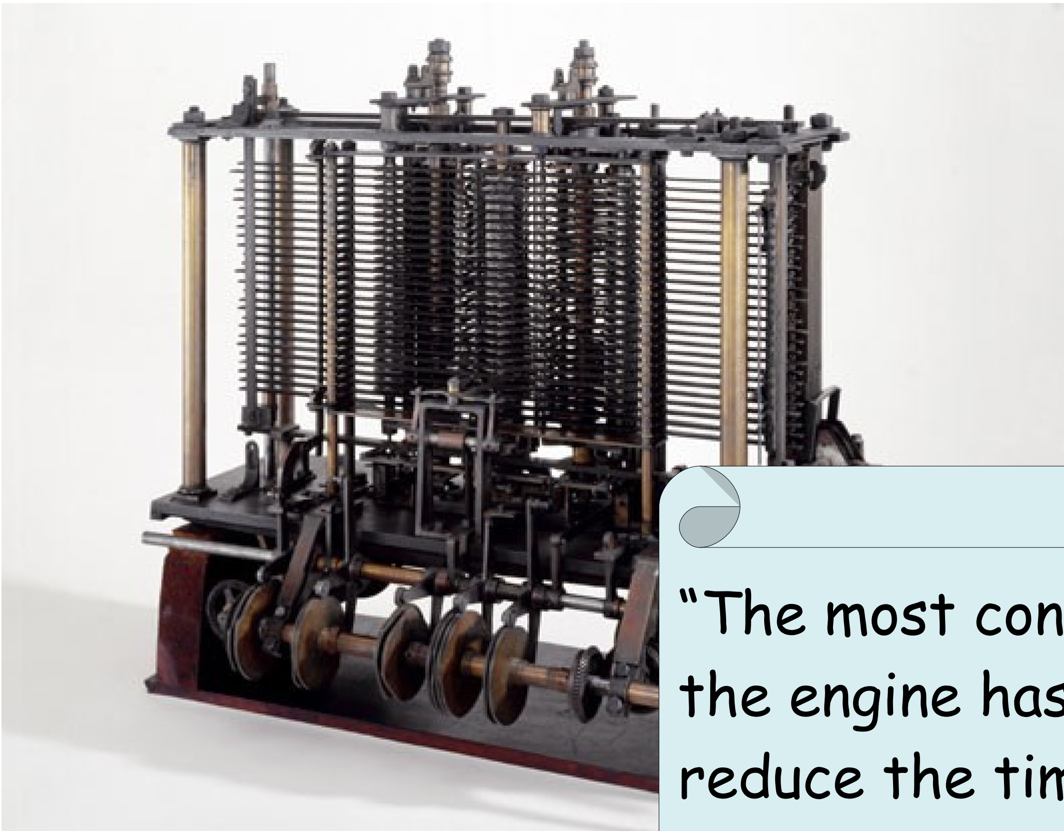
Performance analysis: an old problem

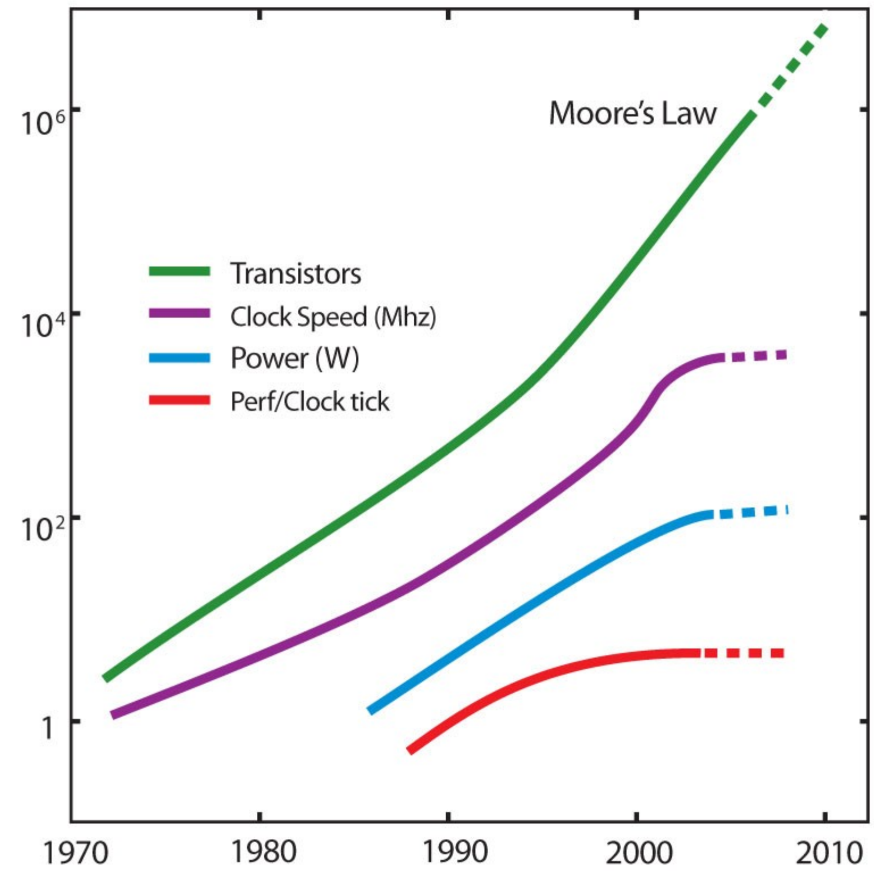


"The most constant difficulty in contriving the engine has arisen from the desire to reduce the time in which the calculations were executed to the shortest which is possible."

Charles Babbage
1791 – 1871

Today: the "free lunch" is over

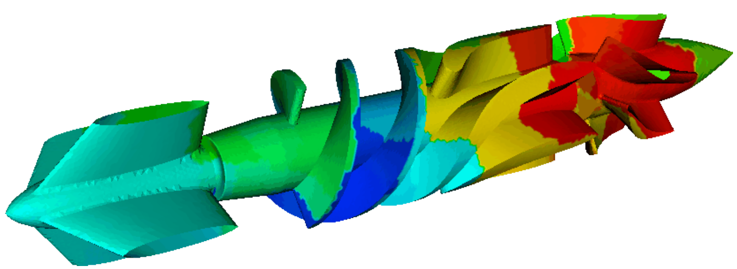
- Moore's law is still in charge, but
  - Clock rates do no longer increase
  - Performance gains only through increased parallelism
- Optimizations of applications more difficult
  - Increasing application complexity
    - *Multi-physics*
    - *Multi-scale*
  - Increasing machine complexity
    - *Hierarchical networks / memory*
    - *More CPUs / multi-core*



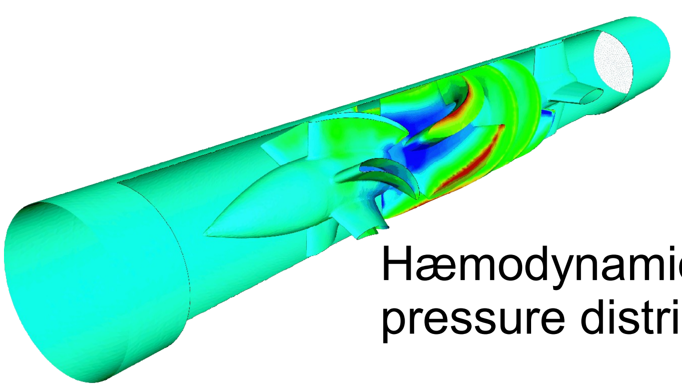
➠ Every doubling of scale reveals a new bottleneck!

Example: XNS

- CFD simulation of unsteady flows
  - Developed by CATS / RWTH Aachen
  - Exploits finite-element techniques, unstructured 3D meshes, iterative solution strategies
- MPI parallel version
  - >40,000 lines of Fortran & C
  - DeBakey blood-pump data set (3,714,611 elements)

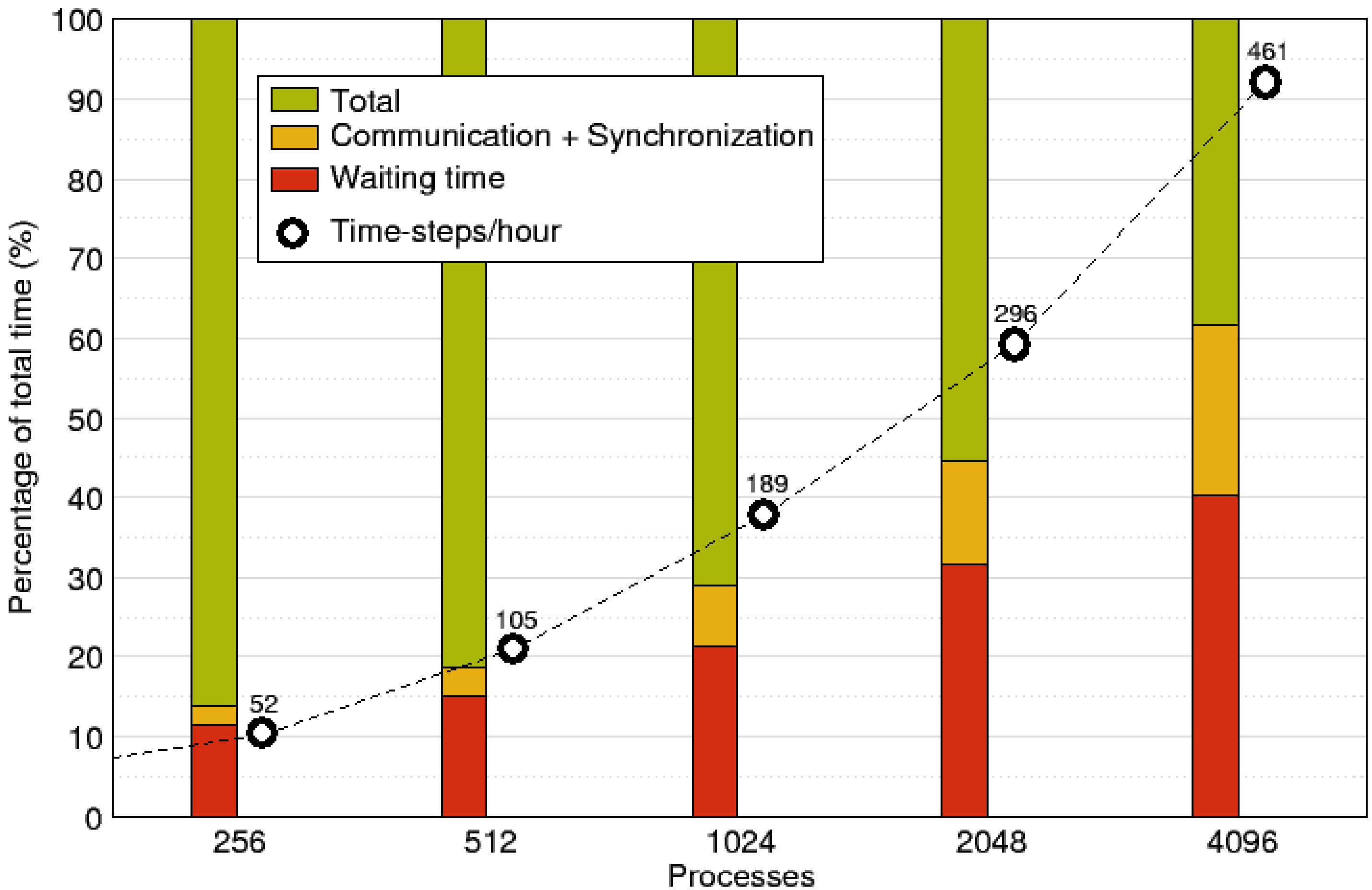


Partitioned finite-element mesh



Hæmodynamic flow pressure distribution

XNS wait-state analysis on BG/L (2007)



Outline

- Motivation
- Performance analysis basics
    - Terminology
    - Techniques
- Performance tools overview
- Outlook

Performance factors of parallel applications

- “Sequential” factors
  - Computation
    - ➠ *Choose right algorithm, use optimizing compiler*
  - Cache and memory
    - ➠ *Tough! Only limited tool support, hope compiler gets it right*
  - Input / output
    - ➠ *Often not given enough attention*
- “Parallel” factors
  - Communication (i.e., message passing)
  - Threading
  - Synchronization
    - ➠ *More or less understood, good tool support*

Tuning basics

- Successful tuning is a combination of
  - The right algorithms and libraries
  - Compiler flags and directives
  - Thinking !!!
- Measurement is better than guessing
  - To determine performance bottlenecks
  - To validate tuning decisions and optimizations

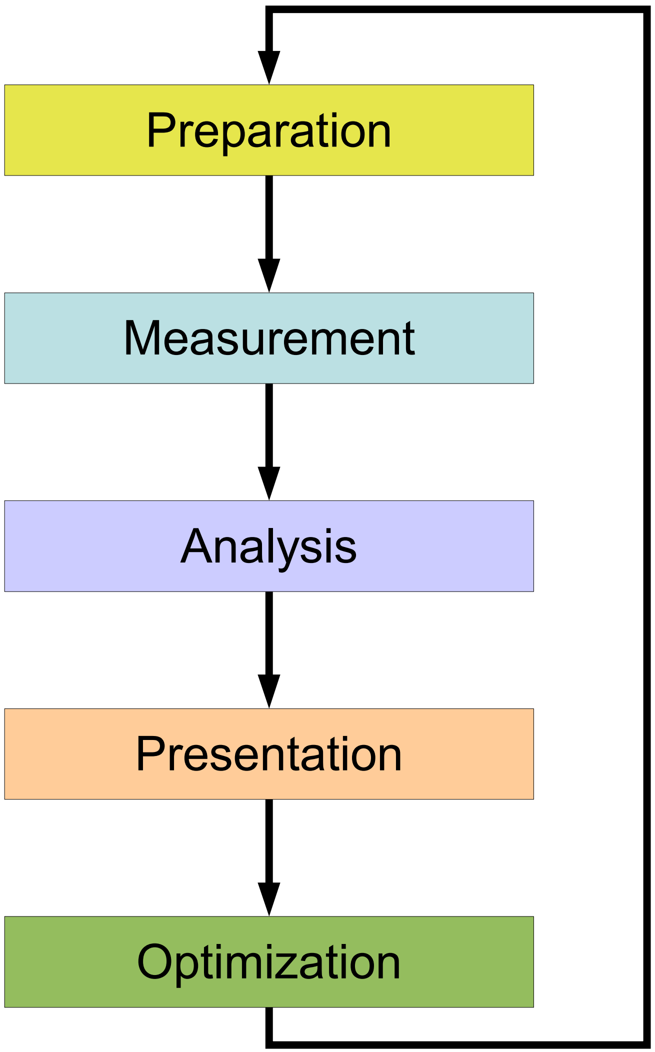
    ➠ *After each step!*

However ...

> "We should forget about small efficiencies, say 97% of the time: premature optimization is the root of all evil."
>
> Donald Knuth

- It's easier to optimize a slow correct program than to debug a fast incorrect one
  - ➠ *Nobody cares how fast you can compute the wrong answer...*

Performance analysis workflow



- Prepare application, insert extra code (probes/hooks)
- Collection of data relevant to performance analysis
- Calculation of metrics, identification of performance metrics
- Visualization of results in an intuitive/understandable form
- Elimination of performance problems

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The 80/20 rule

- Programs typically spend 80% of their time in 20% of the code
- Programmers typically spend 20% of their effort to get 80% of the total speedup possible for the application
  - *Know when to stop!*
- Don't optimize what does not matter
  - *Make the common case fast!*

> "If you optimize everything,
> you will always be unhappy."
>
> Donald E. Knuth

Metrics of performance

- What can be measured?
  - A **count** of how many times an event occurs
    - *E.g., the number of MPI point-to-point messages sent*
  - The **duration** of some time interval
    - *E.g., the time spent in these send calls*
  - The **size** of some parameter
    - *E.g., the number of bytes transmitted by these calls*
- Derived metrics
  - E.g., rates / throughput
  - Needed for normalization

Example metrics

- Execution time
- Number of function calls
- CPI
  - Clock ticks per instruction
- MFLOPS
  - Millions of floating-point operations executed per second

"math" Operations?
HW Operations?
HW Instructions?
32-/64-bit? …

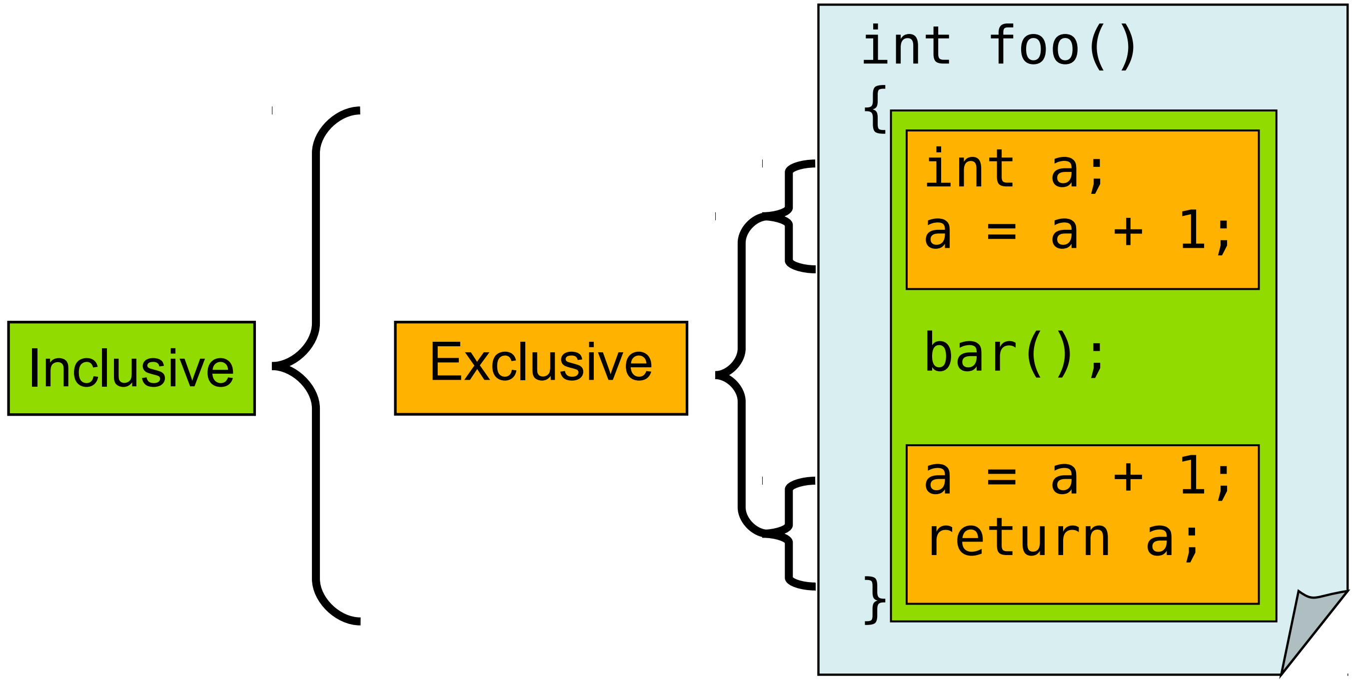
Execution time

- Wall-clock time
  - Includes waiting time: I/O, memory, other system activities
  - In time-sharing environments also the time consumed by other applications
- CPU time
  - Time spent by the CPU to execute the application
  - Does not include time the program was context-switched out
    - *Problem: Does not include inherent waiting time (e.g., I/O)*
    - *Problem: Portability? What is user, what is system time?*

- Problem: Execution time is non-deterministic
  - Use mean or minimum of several runs

Inclusive vs. Exclusive values

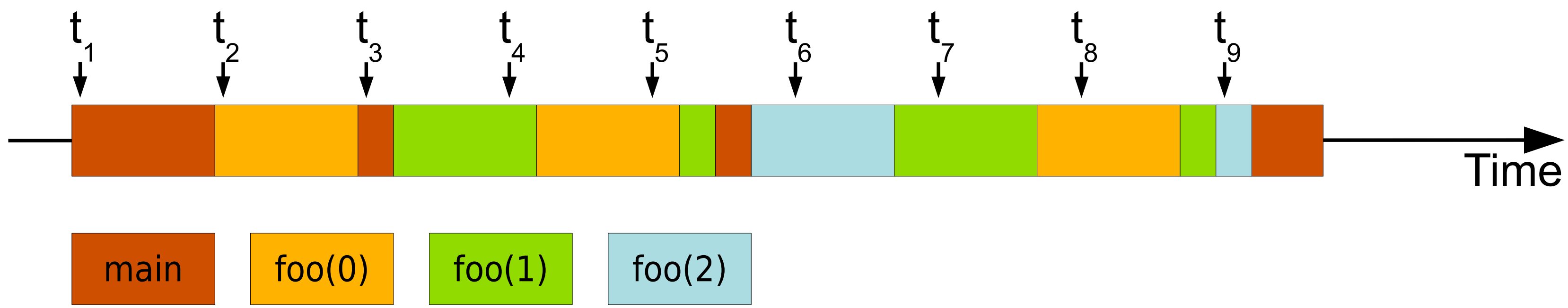
- Inclusive
  - Information of all sub-elements aggregated into single value
- Exclusive
  - Information cannot be split up further



Classification of measurement techniques

- When are performance measurements triggered?
  - Sampling
  - Code instrumentation
- How is performance data recorded?
  - Profiling / Runtime summarization
  - Tracing

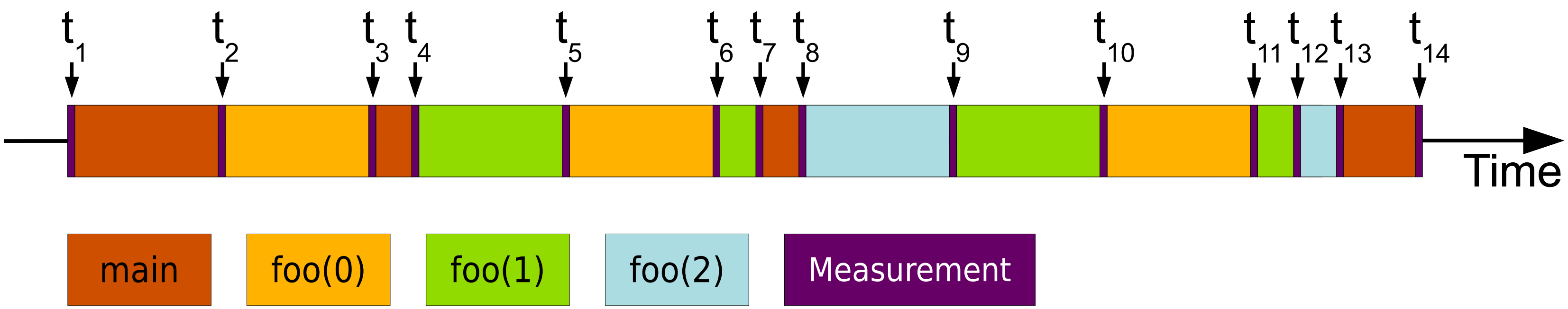
Sampling




```
int main()
{
    int i;

    for (i=0; i < 3; i++)
        foo(i);

    return 0;
}

void foo(int i)
{

    if (i > 0)
        foo(i – 1);

}
```

- Running program is interrupted periodically
  - Timer interrupt, OS signal, or HWC overflow
  - Service routine examines return-address stack
  - Addresses are mapped to routines using symbol table information
- **Statistical** inference of program behavior
  - Not very detailed information on highly volatile metrics
  - Requires long-running applications
- Works with unmodified executable, but symbol table information is generally recommended

Instrumentation




```
int main()
{
    int i;
    Enter("main");
    for (i=0; i < 3; i++)
        foo(i);
    Leave("main");
    return 0;
}

void foo(int i)
{
    Enter("foo");
    if (i > 0)
        foo(i – 1);
    Leave("foo");
}
```

- Measurement code is inserted such that every interesting event is **directly** captured
  - Can be done in various ways
- Advantage:
  - Much more detailed information
- Disadvantage:
  - Processing of source-code / executable necessary
  - Large relative overheads for small functions

Instrumentation techniques

- Static instrumentation
  - Program is instrumented prior to execution
- Dynamic instrumentation
  - Program is instrumented at runtime

- Code is inserted
  - Manually
  - Automatically
    - *By a preprocessor / source-to-source translation tool*
    - *By a compiler*
    - *By linking against a pre-instrumented library / runtime system*
    - *By binary-rewrite / dynamic instrumentation tool*

Critical issues

- Accuracy
  - Perturbation
    - *Measurement alters program behavior*
    - *E.g., memory access pattern*
  - Intrusion overhead
    - *Measurement itself needs time and thus lowers performance*
  - Accuracy of timers & counters
- Granularity
  - How many measurements?
  - How much information / work during each measurement?

➠ *Tradeoff: Accuracy vs. Expressiveness of data*

Classification of measurement techniques

- When are performance measurements triggered?
  - Sampling
  - Code instrumentation

- How is performance data recorded?
  - Profiling / Runtime summarization
  - Tracing

Profiling / Runtime summarization

- Recording of aggregated information
  - Time
  - Counts
    - *Function calls*
    - *Hardware counters*
- Over program and system entities
  - Functions, call sites, basic blocks, loops, …
  - Processes, threads

➠ *Profile = summation of events over time*

Types of profiles

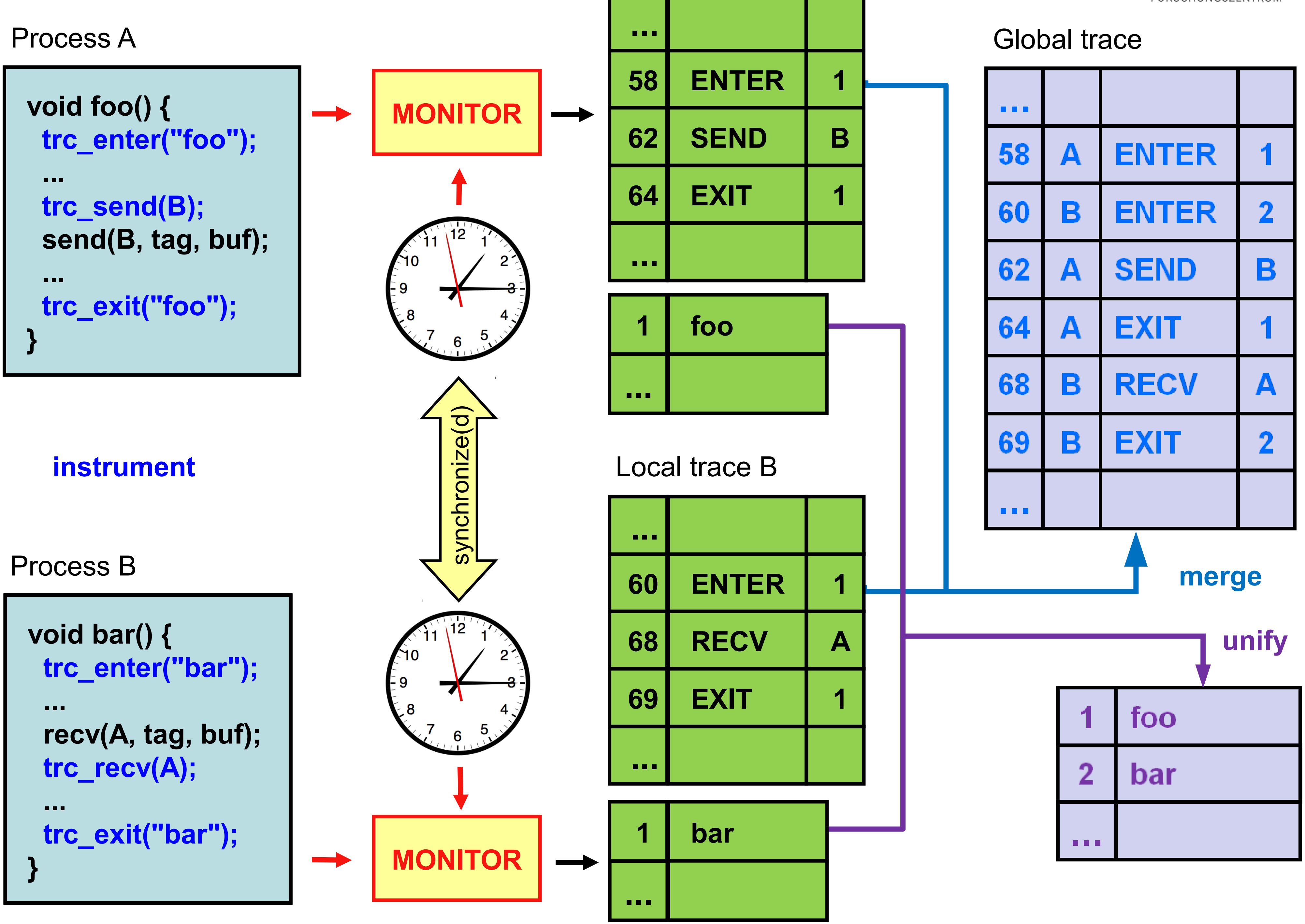
- Flat profile
  - Shows distribution of metrics per function / instrumented region
  - Calling context is not taken into account
- Call-path profile
  - Shows distribution of metrics per call path
  - Sometimes only distinguished by partial calling context (e.g., two levels)
- Special-purpose profiles
  - Focus on specific aspects, e.g., MPI calls or OpenMP constructs

Tracing

- Recording information about significant points (events) during execution of the program
  - Enter / leave of a region (function, loop, …)
  - Send / receive a message, …
- Save information in event record
  - Timestamp, location, event type
  - Plus event-specific information (e.g., communicator, sender / receiver, …)
- Abstract execution model on level of defined events

➠ *Event trace = Chronologically ordered sequence of event records*

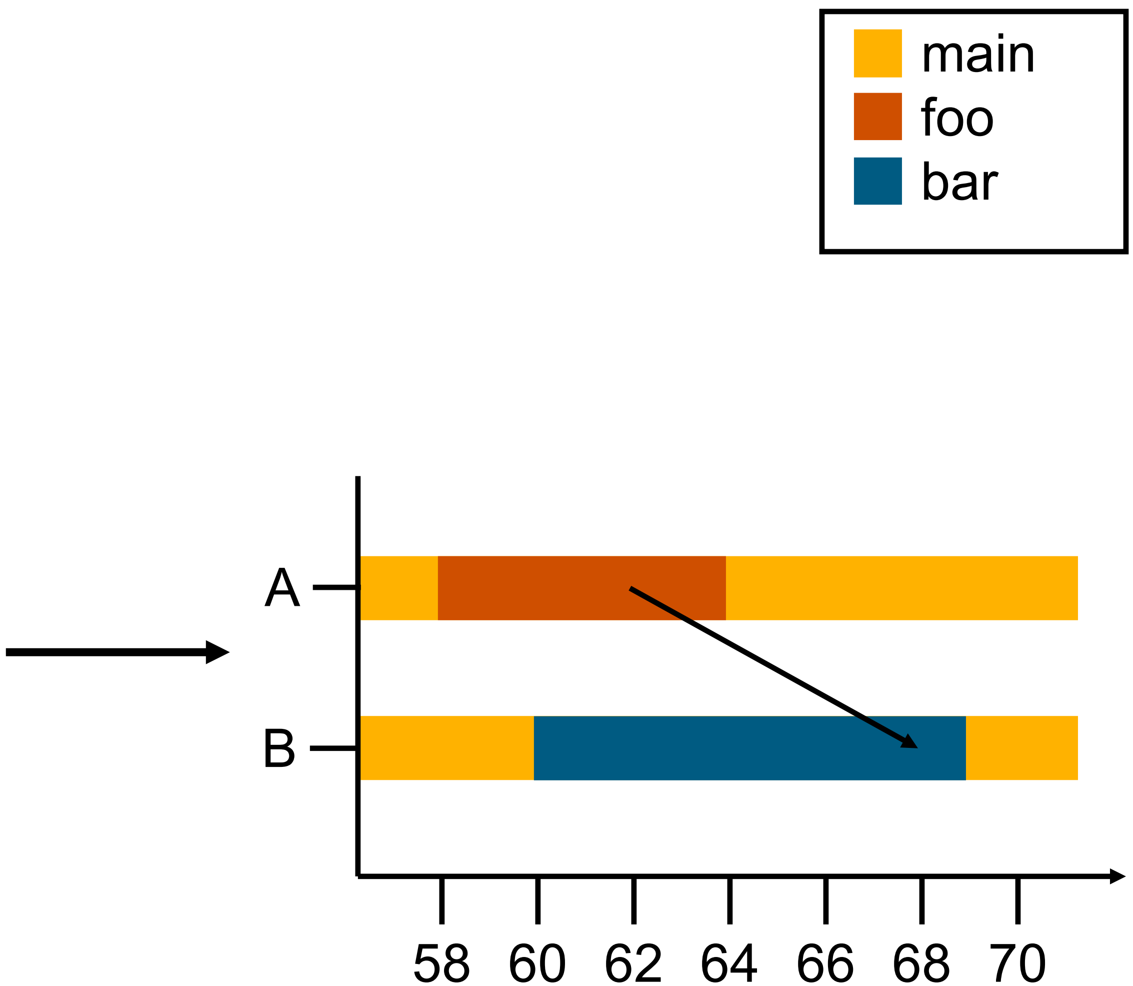
Event tracing



Example: Time-line visualization

1	foo
2	bar
3	...

...			
58	A	ENTER	1
60	B	ENTER	2
62	A	SEND	B
64	A	EXIT	1
68	B	RECV	A
69	B	EXIT	2
...			



Tracing vs. Profiling

- Tracing advantages
  - Event traces preserve the **temporal** and **spatial** relationships among individual events (➠ context)
  - Allows reconstruction of **dynamic** application behavior on any required level of abstraction
  - Most general measurement technique
    - *Profile data can be reconstructed from event traces*
- Disadvantages
  - Traces can become very large
  - Writing events to file at runtime causes perturbation
  - Writing tracing software is complicated
    - *Event buffering, clock synchronization, ...*

No single solution is sufficient!

➠ *A combination of different methods, tools and techniques is typically needed!*

- Measurement
  - *Sampling / instrumentation, profiling / tracing, ...*
- Instrumentation
  - *Source code / binary, manual / automatic, ...*
- Analysis
  - *Statistics, visualization, automatic analysis, data mining, ...*

Typical performance analysis procedure

- Do I have a performance problem at all?
  - Time / speedup / scalability measurements
- What is the main bottleneck (computation / communication)?
  - MPI / OpenMP / flat profiling
- Where is the main bottleneck?
  - Call-path profiling, detailed basic block profiling
- Why is it there?
  - Hardware counter analysis, trace selected parts to keep trace size manageable
- Does my code have scalability problems?
  - Load imbalance analysis, compare profiles at various sizes function-by-function

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Fall-back: “Home-grown performance tool”

- Simple measurements can always be performed
  - C/C++: times(), clock(), gettimeofday(), clock_gettime(), getrusage()
  - Fortran: etime, cpu_time, system_clock
- However, ...
  - Use these functions rarely and only for coarse-grained timings
  - Avoid do-it-yourself solutions for detailed measurements
  - Use dedicated tools instead
    - *Typically more powerful*
    - *Might use platform-specific timers with better resolution and/or lower overhead*

GNU gprof

- Shows where the program spends its time
  - Indicates which functions are candidates for tuning
  - Identifies which functions are being called
  - Can be used on large and complex programs
- Method
  - Compiler inserts code to count each function call (compile with “-pg”)
    - *Shows up in profile as “__mcount”*
  - Time information is gathered using sampling
    - *Current function and and its parents (two levels) are determined*
  - Program execution generates “gmon.out” file
  - To dump human-readable profile to stdout, call

```
gprof <executable> <gmon.out file>
```

GNU gprof: flat profile

```
Each sample counts as 0.01 seconds.
  %   cumulative   self              self     total
 time   seconds   seconds    calls  ms/call  ms/call  name
 82.90     31.55    31.55    27648     1.14     1.14  pc_jac2d_blk3_
  7.54     34.42     2.87        1  2870.00 37910.00  cg3_blk_
  5.96     36.69     2.27    28672     0.08     0.08  matxvec2d_
  2.13     37.50     0.81    55296     0.01     0.01  dot_prod2d_
  0.87     37.83     0.33       54     6.11     6.11  add_exchange2d_
  0.34     37.96     0.13                             main
  0.21     38.04     0.08       27     2.96     2.96  cs_jac2d_blk3_
...
```

- Avg. inclusive time
- Avg. exclusive time
- Number of calls
- Exclusive time (sorting criterion)
- Time sum
- Percentage of total time

GNU gprof: (partial) call-path profile

```
                                   called/total    parents
index %time   self descendents   called+self    name            index
                                   called/total    children

              0.17        2.83        1/1             .__start [2]
[1]     99.3  0.17        2.83        1           .main [1]
              2.83        0.00       10/10            .relax [3]
              0.00        0.00        3/13            .printf [15]
              0.00        0.00        1/1             .saveOutput [27]
              0.00        0.00        2/1523          .malloc [5]
              0.00        0.00        1/1             .readInput [40]
              0.00        0.00       10/20            .update [68]

...
```

- Percentage of total time (sorting criterion)
- Exclusive time
- Time spent in children
- Number of calls from this callsite
- Total number of calls
- Children (Called functions)
- Parent (Callsite)

OpenMP profiling: ompP

- Light-weight OpenMP profiling tool
- Reports execution times and counts for various OpenMP constructs
  - Presented in terms of the user model, not the system model
- Provides additional analyses
- Relies on source-code instrumentation
  - Re-compilation necessary
- License: GPL-2

- Web site: http://www.ompp-tool.com

ompP: advanced analyses

- Overhead analysis
  - Four well-defined overhead categories of parallel execution
    - *Imbalance, Synchronization, Limited parallelism, Thread management*
  - Analysis for individual parallel regions or whole program
- Scalability analysis
  - Analyze overheads for increasing thread counts
- Performance properties detection
  - Automatically detect common inefficiency situations
- Incremental profiling
  - Profiling-over-time adds temporal dimension

ompP: text output example

- Flat OpenMP construct profile

```
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            159
   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
```

- Call-path profile

```
Incl. CPU time
  32.22 (100.0%)             [APP 4 threads]
  32.06 (99.50%)  PARALLEL  +-R00004 main.c (42-46)
  10.02 (31.10%)   USERREG     |-R00001 main.c (19-21) ('foo1')
  10.02 (31.10%)  CRITICAL     |  +-R00003 main.c (33-36) (unnamed)
  16.03 (49.74%)   USERREG     +-R00002 main.c (26-28) ('foo2')
  16.03 (49.74%)  CRITICAL        +-R00003 main.c (33-36) (unnamed)
```

MPI profiling: mpiP

- Scalable, light-weight MPI profiling library
- Generates detailed text summary of MPI behavior
  - Time spent in each MPI function call site
  - Bytes sent by each MPI function call site (if applicable)
  - MPI I/O statistics
  - Configurable traceback depth for function call sites
- Controllable from program using MPI_Pcontrol()
  - Allows to profile just one code module or a single iteration
- Uses standard PMPI interface: only re-linking of application necessary
- License: new BSD
- Web site: http://mpip.sourceforge.net

mpiP: text output example

```
@ mpiP
@ Version: 3.1.1
// 10 lines of mpiP and experiment configuration options
// 8192 lines of task assignment to BlueGene topology information

@--- MPI Time (seconds) ---------------------------------------
Task    AppTime    MPITime     MPI%
   0       37.7       25.2    66.89
// ...
8191       37.6         26    69.21
   *   3.09e+05   2.04e+05    65.88

@--- Callsites: 26 -------------------------------------------
 ID Lev File/Address      Line Parent_Funct             MPI_Call
  1   0 coarsen.c          542 hypre_StructCoarsen      Waitall
// 25 similiar lines

@--- Aggregate Time (top twenty, descending, milliseconds) --------
Call                 Site       Time    App%    MPI%     COV
Waitall                21   1.03e+08   33.27   50.49    0.11
Waitall                 1   2.88e+07    9.34   14.17    0.26
// 18 similiar lines
```

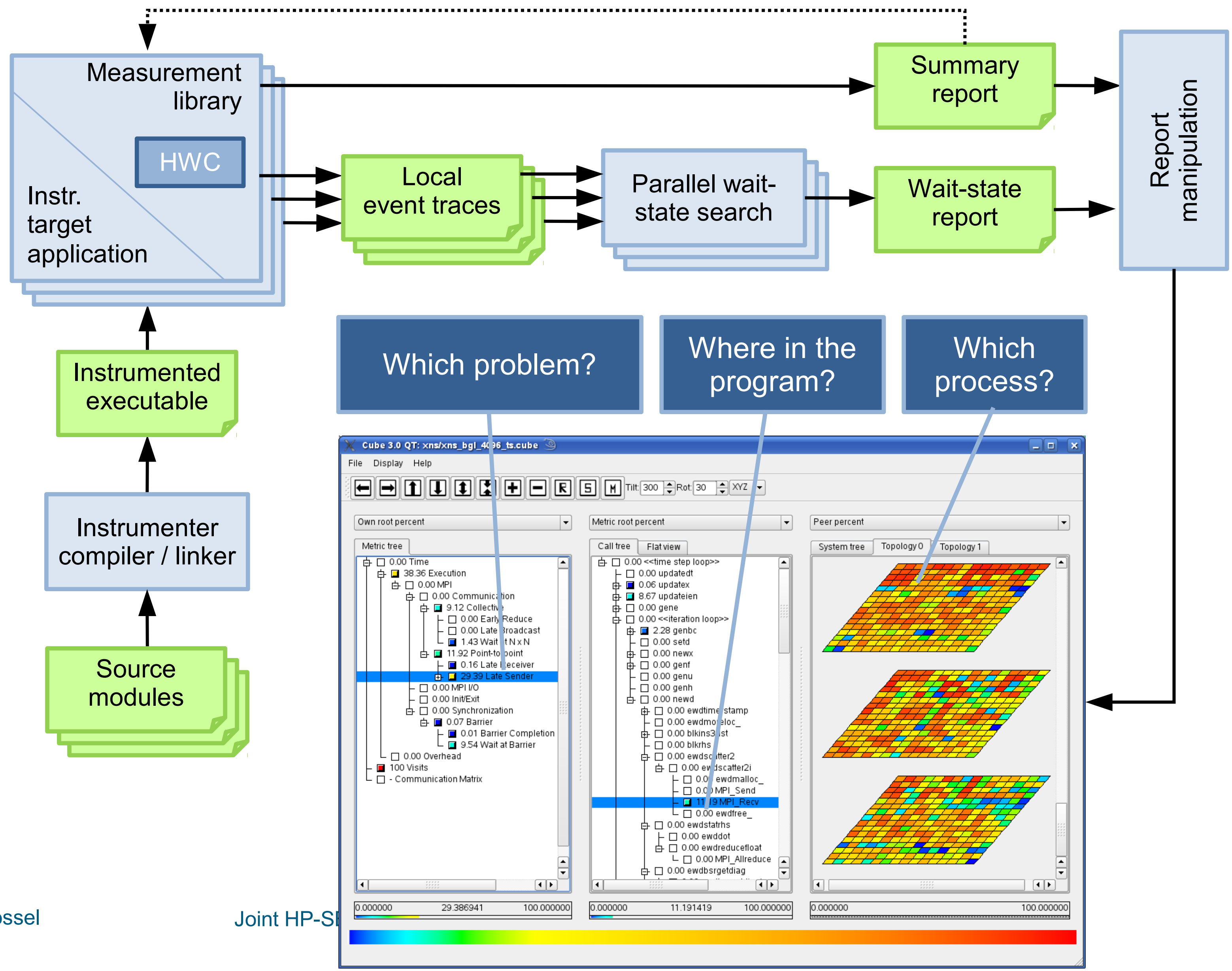
mpiP: text output example (cont.)

```
@--- Aggregate Sent Message Size (top twenty, descending, bytes) --
Call                     Site      Count       Total        Avrg  Sent%
Isend                      11  845594460   7.71e+11         912  59.92
Allreduce                  10      49152   3.93e+05           8   0.00
// 6 similiar lines

@--- Callsite Time statistics (all, milliseconds): 212992 ---------
Name          Site Rank      Count     Max    Mean       Min   App%   MPI%
Waitall         21    0     111096     275     0.1  0.000707  29.61  44.27
//   ...
Waitall         21 8191      65799     882    0.24  0.000707  41.98  60.66
Waitall         21    * 577806664     882   0.178  0.000703  33.27  50.49
// 213,042 similiar lines

@--- Callsite Message Sent statistics (all, sent bytes) -----------
Name          Site Rank      Count       Max      Mean   Min        Sum
Isend           11    0      72917 2.621e+05     851.1     8  6.206e+07
//...
Isend           11 8191      46651 2.621e+05      1029     8  4.801e+07
Isend           11    * 845594460 2.621e+05     911.5     8  7.708e+11
// 65,550 similiar lines
```

scalasca

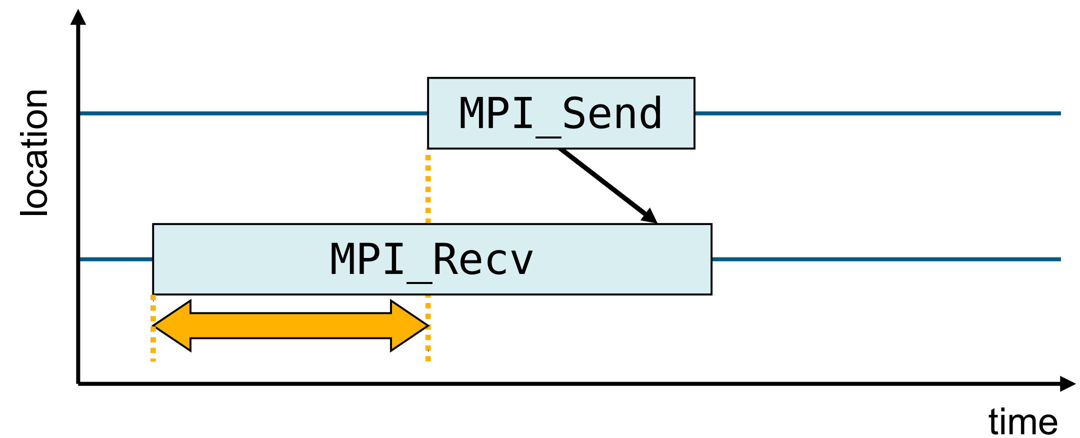
- Scalable performance-analysis toolkit for parallel codes
  - Specifically targeting large-scale applications running on 10,000s to 100,000s of cores
- Integrated performance-analysis process
  - Performance overview via call-path profiles
  - In-depth study of application behavior via event tracing
    - *Automatic trace analysis identifying wait states*
  - Switching between both options without re-compilation or re-linking
- Supports MPI 2.2 and basic OpenMP
- License: new BSD
- Website: http://www.scalasca.org

Scalasca architecture

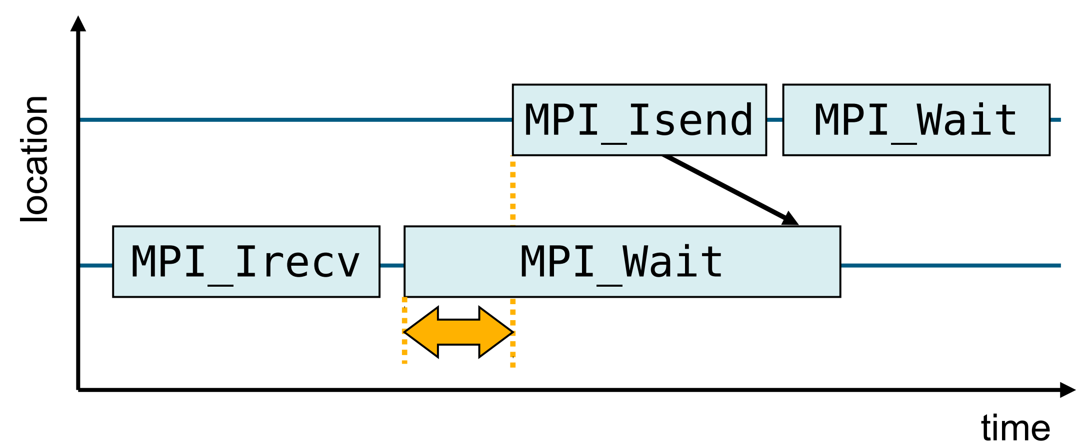


Example pattern: Late sender

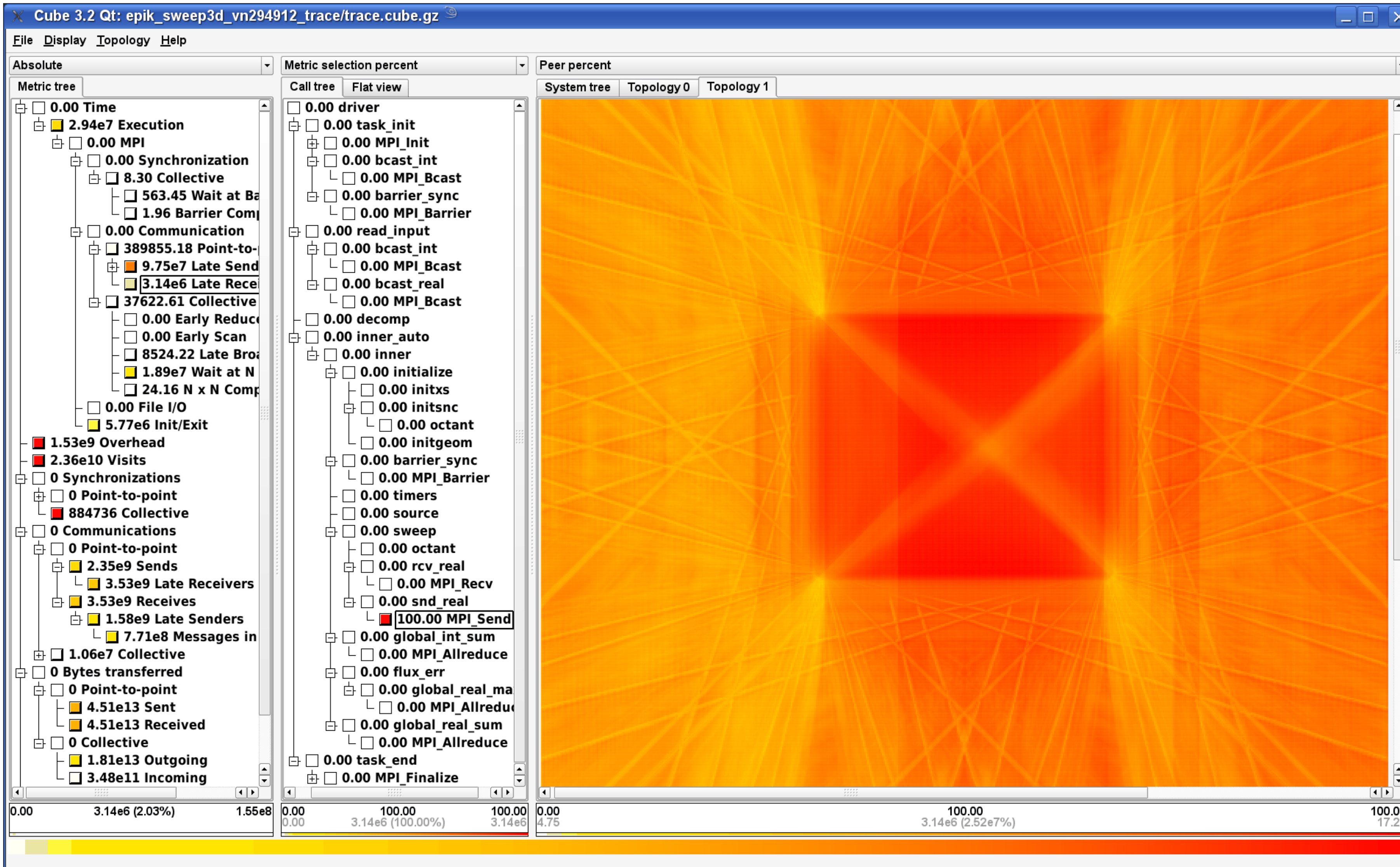
- Blocking receive called earlier than corresponding send operation
  - ➠ Waiting time



- Also applies to non-blocking communication



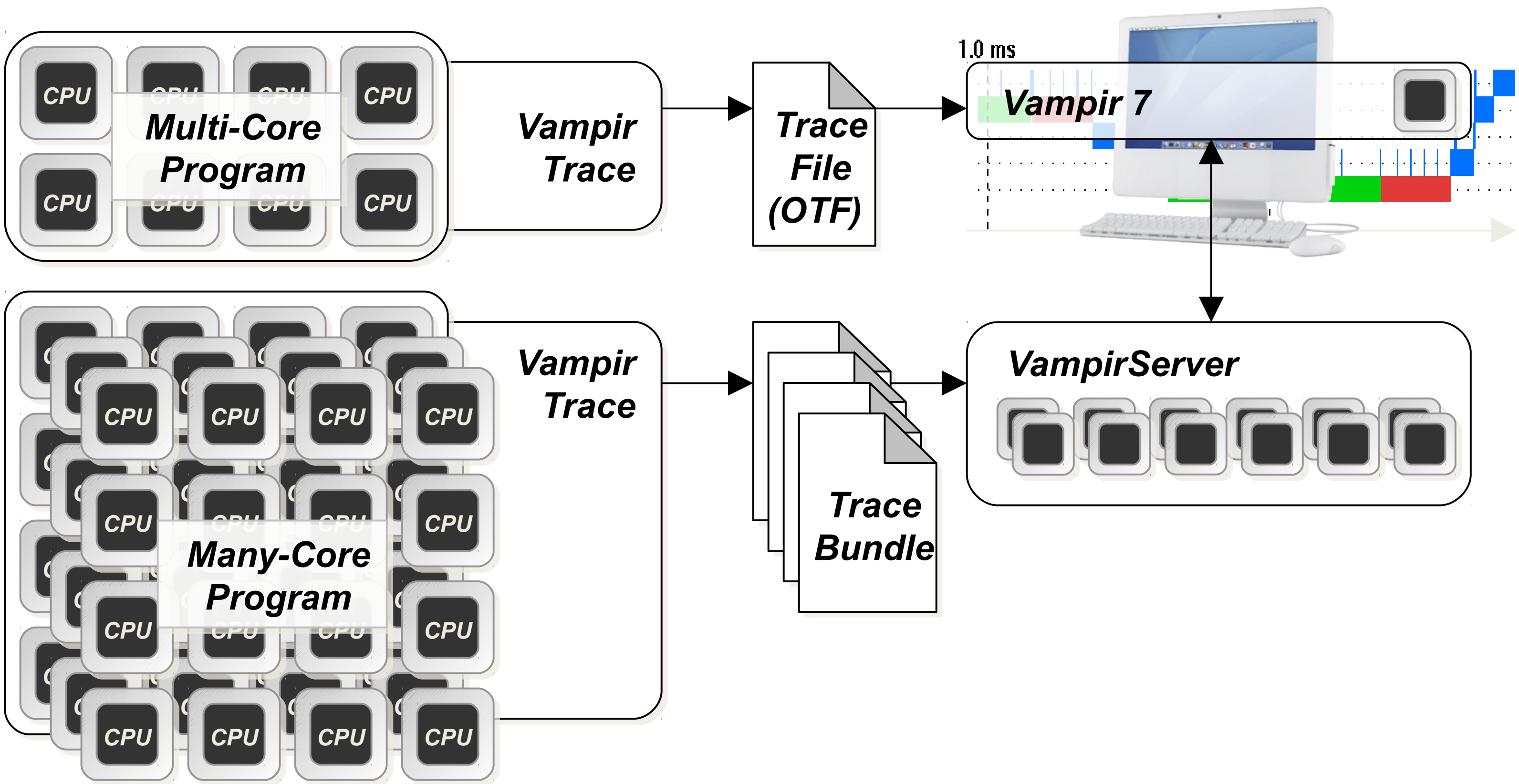
Example: Sweep3D trace analysis on BG/P @ 288k CPUs



VampirTrace / Vampir

- VampirTrace
  - Tool set and runtime library to generate OTF traces
  - Supports MPI, OpenMP, POSIX threads, Java, CUDA, ...
  - Also distributed as part of Open MPI since v1.3
  - License: new BSD
  - Web site: http://www.tu-dresden.de/zih/vampirtrace
- Vampir / VampirServer
  - Interactive trace visualizer with powerful statistics
  - License: commercial
  - Web site: http://www.vampir.eu

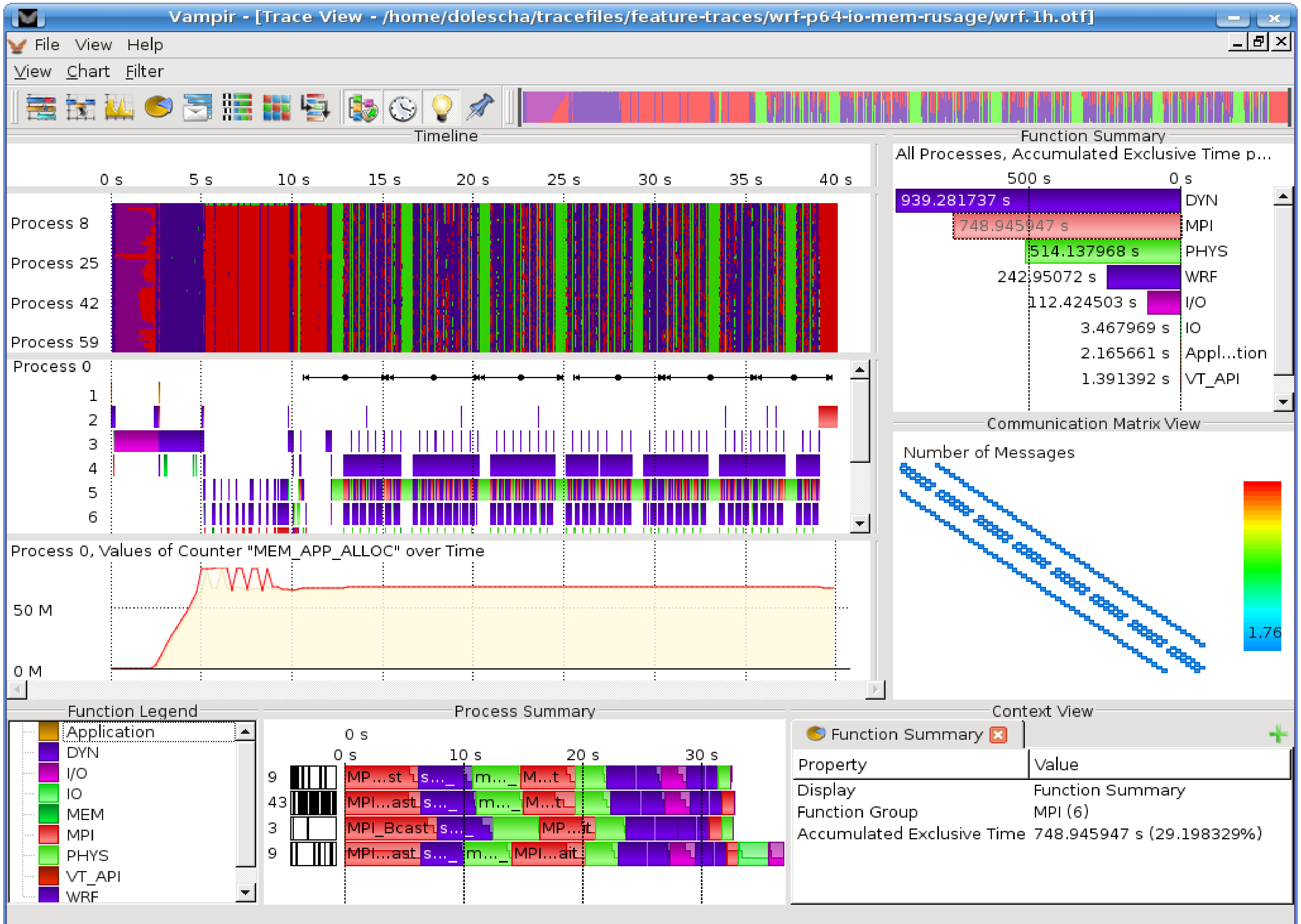
Vampir toolset architecture



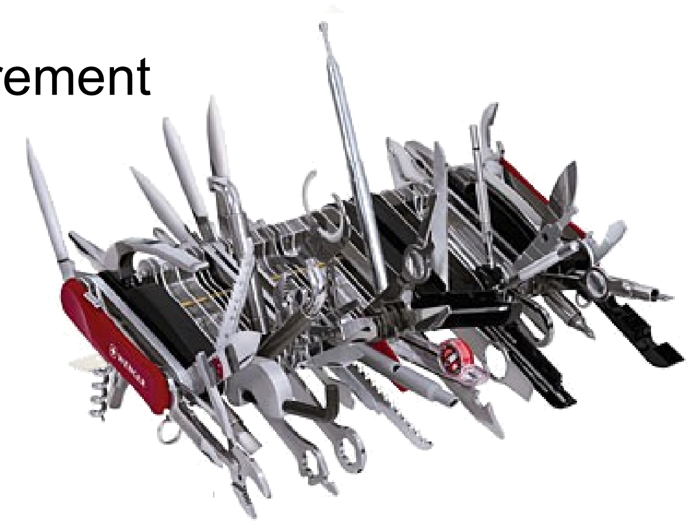
Vampir displays

- The main displays of Vampir are
  - Master time-line
  - Process and counter time-line
  - Function summary
  - Message summary
  - Process summary
  - Communication matrix
  - Call tree
- All displays are coupled
  - Always show the data for the current time interval
  - Interactive zooming updates the displays automatically

Vampir displays overview



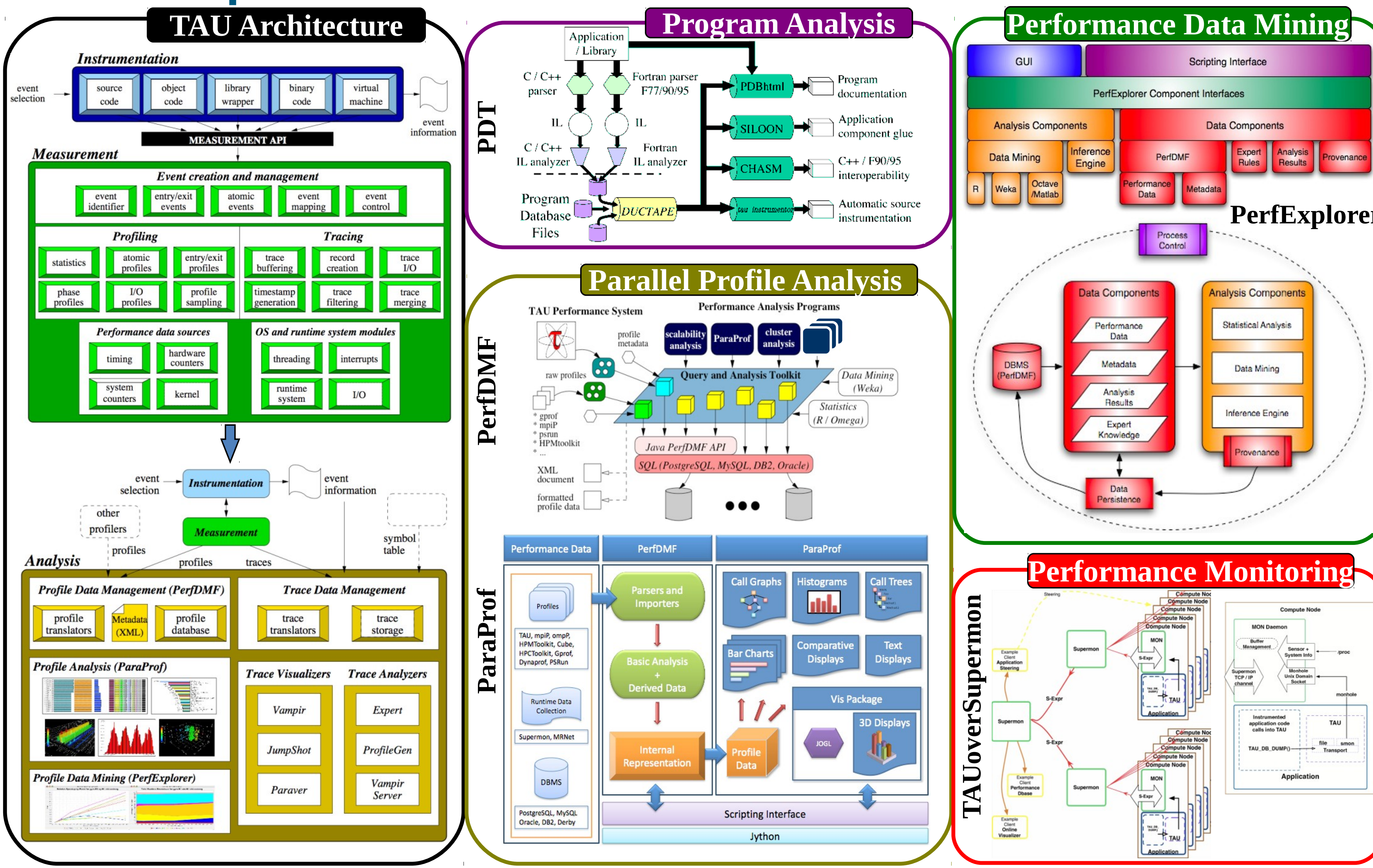
TAU Performance System



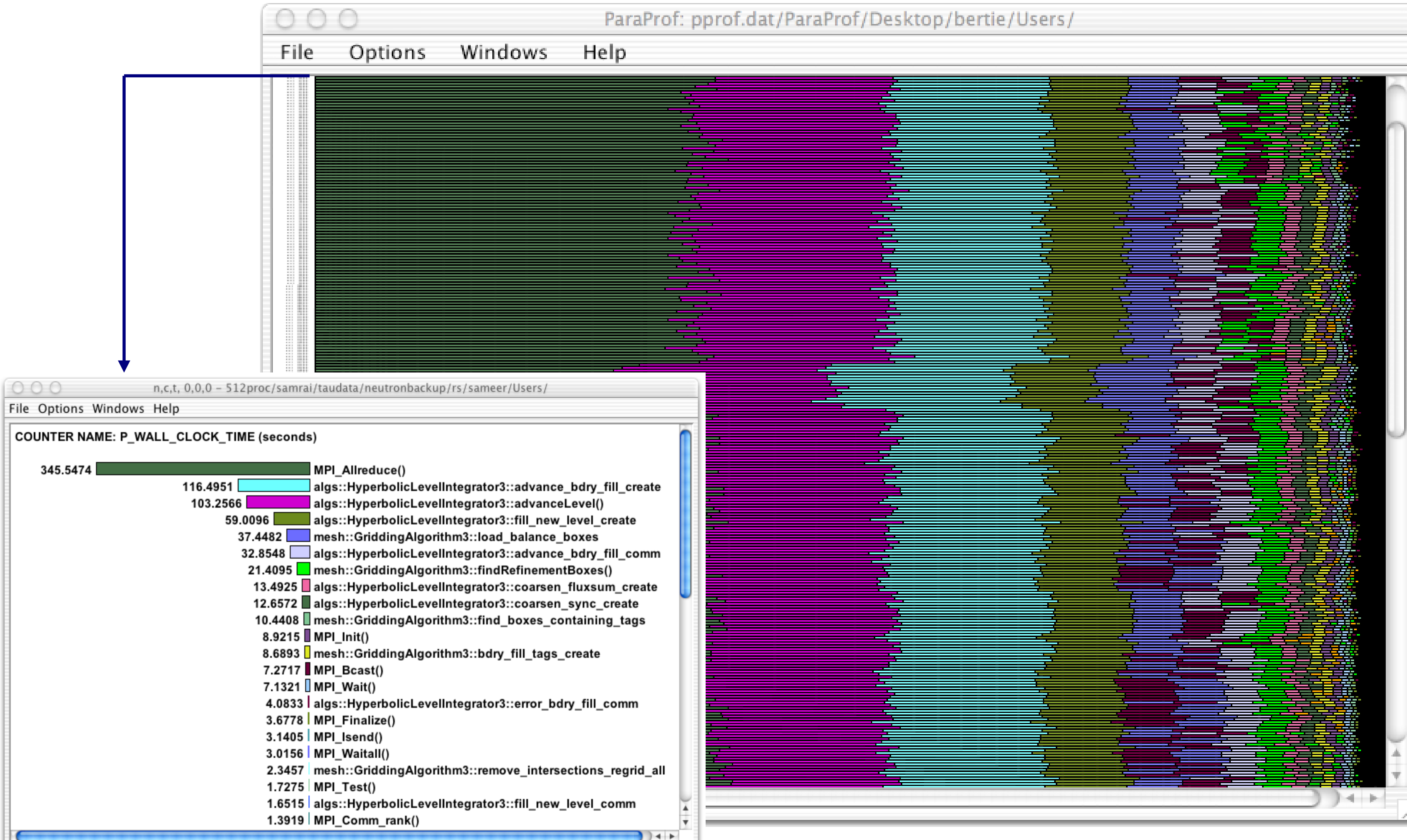
- Very portable tool set for instrumentation, measurement and analysis of parallel applications
- The “swiss army knife” of performance analysis
- Instrumentation API supports choice
  - between profiling and tracing
  - of metrics (e.g., time, HW counter, ...)
- Supports
  - C, C++, Fortran, HPF, HPC++, Java, Python
  - MPI, OpenMP, POSIX threads, Java, Win32, ...
- License: Open-source (historical permission notice and disclaimer)

- Web site: http://tau.uoregon.edu

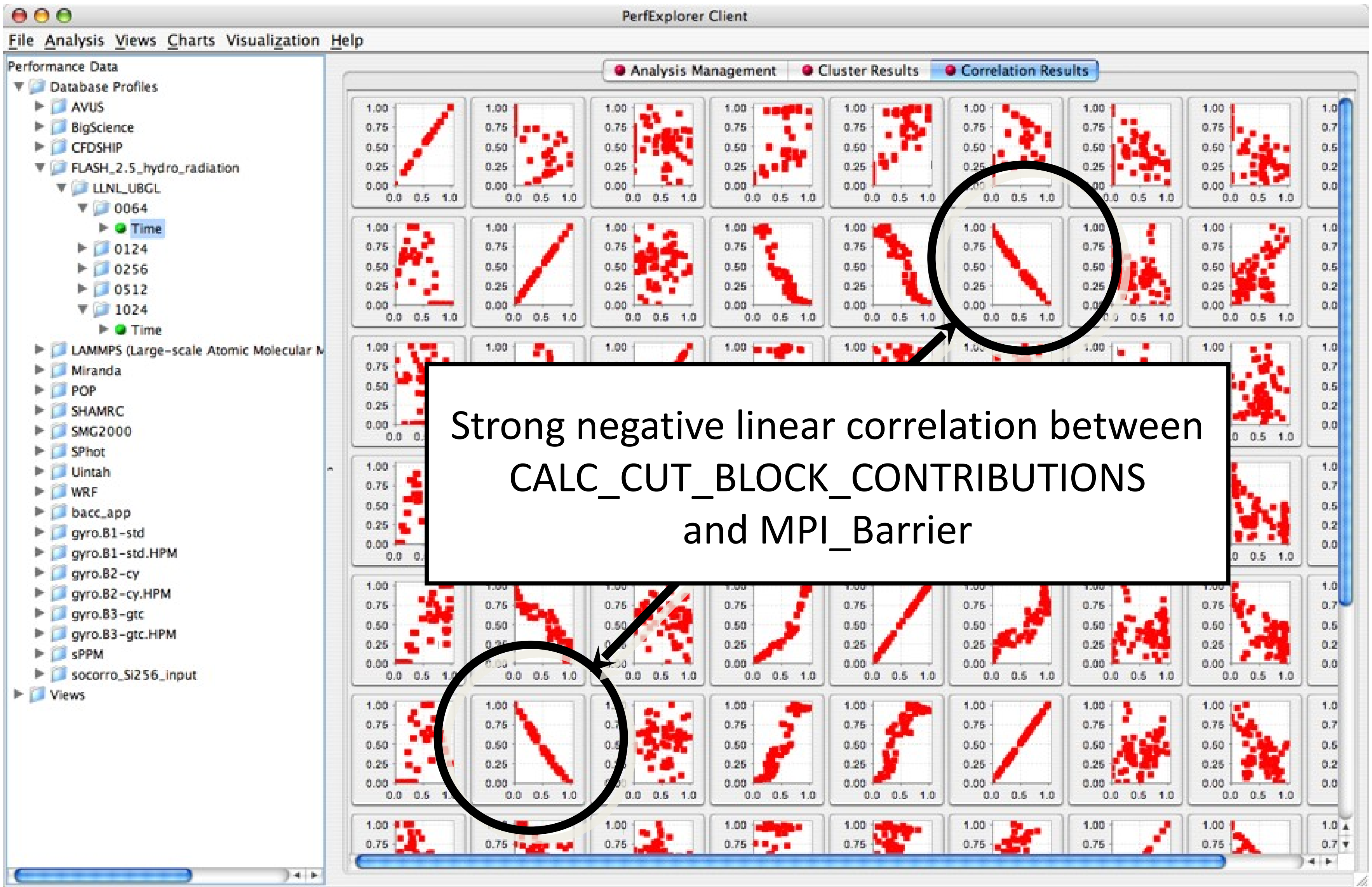
TAU components



TAU profile analysis: ParaProf



TAU data mining: PerfExplorer



Other open-source tools worth mentioning

- Open|SpeedShop
  - Modular and extensible performance analysis tool set
  - Web site: http://www.openspeedshop.org
- HPCToolkit
  - Multi-platform statistical profiling package
  - Web site: http://hpctoolkit.org
- Paraver
  - Trace-based performance-analysis and visualization framework
  - Web site: http://www.bsc.es/paraver
- PerfSuite, Periscope, IPM, ...

Commercial / vendor-specific tools

- Intel VTune (serial/multi-threaded)
- Intel Trace Analyzer and Collector (MPI)
- Cray Performance Toolkit: CrayPat / Apprentice2
- IBM HPC Toolkit
- Oracle Performance Analyzer
- Rogue Wave SlowSpotter / ThreadSpotter
- ...

Upcoming workshops / tutorials

- 4th Workshop on Productivity and Performance (PROPER 2011)
  - at EuroPar 2011 Conference, Bordeaux/France, August 30th, 2011
  - Tools for HPC Application Development
  - See http://www.vi-hps.org/proper2011ws/
- PRACE Summer School: Taking the most out of supercomputers
  - CSC, Espoo, Finland, September 1st, 2011
  - Performance analysis tools for massively parallel applications
- 8th VI-HPS Tuning Workshop
  - GRS, Aachen, Germany, September 5 – 9, 2011
  - Five-day “bring-your-own-code” workshop
  - See http://www.vi-hps.org/vi-hps-tw8/

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