Profiling sequential programs

Key question

- How do I know where my code spends most of its time?
  - This is called “profiling”
  - Many (free and commercial) tools exist
- Baseline tool: GNU gprof
  - Supported by GCC and Intel compilers (and others)
- Linux “perf” infrastructure
- Based on the profile, optimization can be planned
  - Reduction of work
  - Doing work more efficiently

Profiling with gprof

Caveat: all-new profiling tool “gprofng” upcoming!

Profiling with gprof

- Basic sequential profiling tool under Linux: **gprof**
- Compiling for a profiling run

```
$ icx -pg ……
```

- After running the binary, a file **gmon.out** is written to the current directory
- Human-readable output:

```
$ gprof a.out
```

- Inlining should be disabled for profiling
  - But then the executed code isn't what it should be…

Profiling with gprof: Example

- Example with wrapped **`double`** class:

```
class D {
  double d;
public:
  D(double _d=0) : d(_d) {}
  D operator+(const D& o) {
    D r;
    r.d = d+o.d;
    return r;
  }
  operator double() {
    return d;
  }
};
```

Main program:

```
const int n=10000000;
D a[n],b[n];
D sum;

for(int i=0; i<n; ++i)
  a[i] = b[i] = 1.5;

double s = timestamp();
for(int k=0; k<10; ++k) {
  for(int i=0; i<n; ++i)
    sum = sum + a[i] + b[i];
}
```

Profiling with gprof: Example profiler output

- **`icpx -O3 -pg perf.cc`**

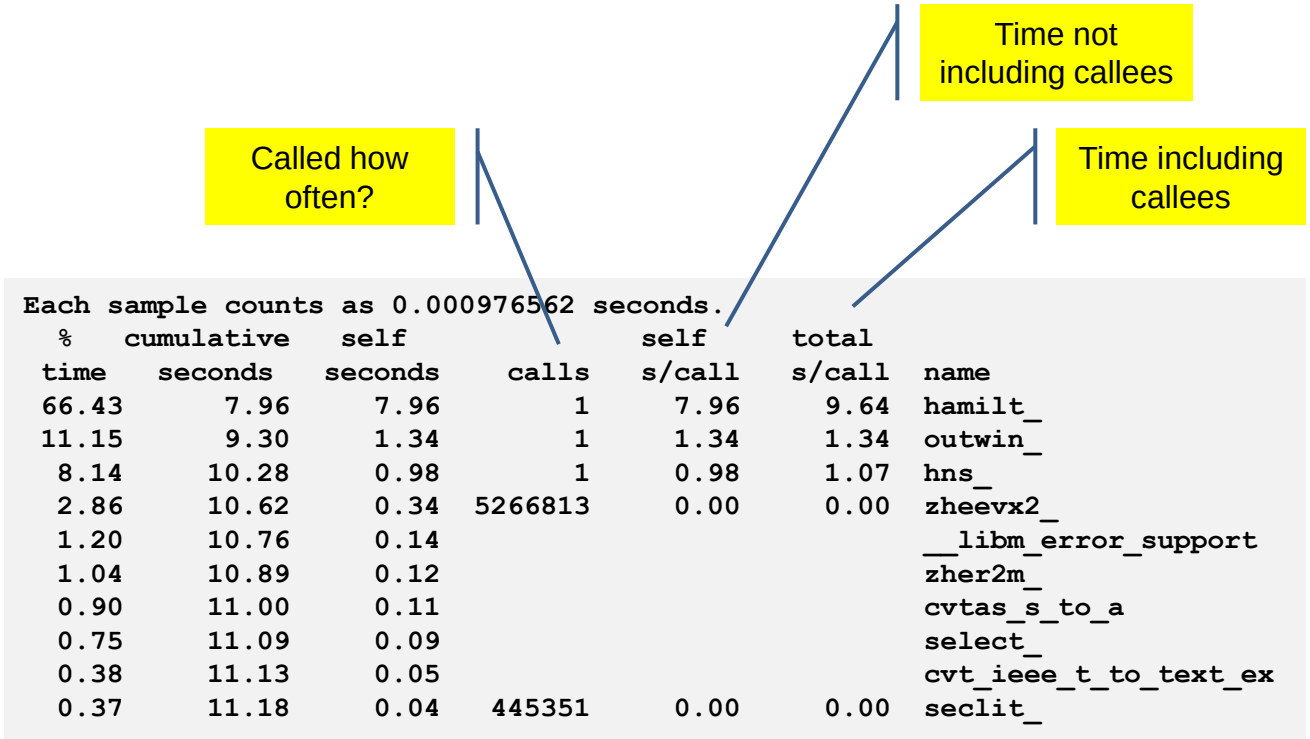
```
  %   cumulative   self              self     total
 time   seconds   seconds    calls  Ts/call  Ts/call  name
101.01      0.41     0.41                             main
```

- **`icpx -O3 -fno-inline -pg perf.cc`**

```
  %   cumulative   self              self     total
 time   seconds   seconds    calls  ns/call  ns/call  name
46.44      0.59     0.59 200000000     2.93     4.48  D::operator+(D const&)
29.63      0.96     0.37 240000001     1.56     1.56  D::D(double)
24.82      1.27     0.31                             main
```

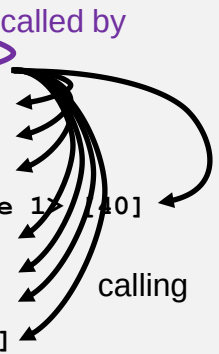
- But where did the time *actually* go?
  - Butterfly (callgraph) profile also available
  - Real problem also with use of libraries (STL!)
  - Sometimes you have to roll your own little profiler (see later!)

Flat profile



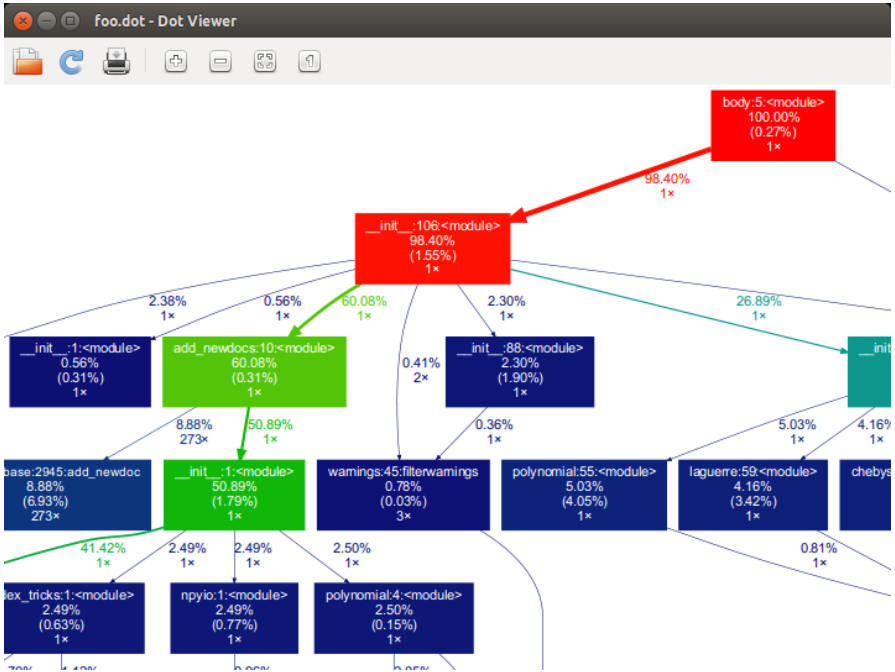
Butterfly (call graph) profile

```
granularity: each sample hit covers 2 byte(s) for 20.00% of 0.05 seconds
index % time    self  children    called     name
                                             <spontaneous>
[1]     100.0    0.00    0.05                 start [1]
                 0.00    0.05       1/1       main [2]
                 0.00    0.00       1/2       on_exit [28]
                 0.00    0.00       1/1       exit [59]
-----------------------------------------------
                 0.00    0.05       1/1       start [1]
[2]     100.0    0.00    0.05       1         main [2]
                 0.00    0.05       1/1       report [3]
-----------------------------------------------
                 0.00    0.05       1/1       main [2]
[3]     100.0    0.00    0.05       1         report [3]
                 0.00    0.03       8/8       timelocal [6]
                 0.00    0.01       1/1       print [9]
                 0.00    0.01       9/9       fgets [12]
                 0.00    0.00      12/34      strncmp <cycle 1> [40]
                 0.00    0.00       8/8       lookup [20]
                 0.00    0.00       1/1       fopen [21]
                 0.00    0.00       8/8       chewtime [24]
                 0.00    0.00       8/16      skipspace [44]
```



Visualizing the butterfly profile

- Gprof2Dot converts gprof output to graphviz “dot” file
  - https://github.com/jrfonseca/gprof2dot
- View dot file with, e.g., xdot



Profiling MPI programs with gprof

- By design, gprof is a tool for serial code
  - It can, however, be convinced to write a trace file that contains the PID in its name

```
$ GMON_OUT_PREFIX=foo mpirun -np 5 ./a.out
[…]
$ ls
a.out  foo.28219  foo.28220  foo.28221  foo.28222  foo.28223
$ gprof a.out foo.28219
```

  - Accumulating individual files:

```
$ gprof --sum a.out foo.*   # generates gmon.sum
$ gprof a.out gmon.sum
```

  - Take care – all values are summed up across processes!

Sampling-based profiling with Linux perf

Sampling

- Interrupts program in regular intervals
- Records data
  - Where is the program right now (address of “current” instruction)?
    - program function
    - line of code
    - machine instruction
  - What does the call stack look like?
    - How did execution get “here”?
- Results
  - Histogram of “how much time spent where”
  - How much time is spent along a particular call path

Advantages vs. gprof:

- *Works on any binary without recompile*
- *Also captures OS and runtime symbols*
- *Also works with multi-threaded code*

Simple runtime profile with Linux perf

Compile with (Intel compiler; options also work for GCC):

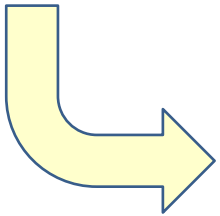
```
$ icx -g -fno-inline -fno-omit-frame-pointer ...
```

Call executable wrapped with perf, generated file **perf.data**:

```
$ perf record -g ./a.out
```

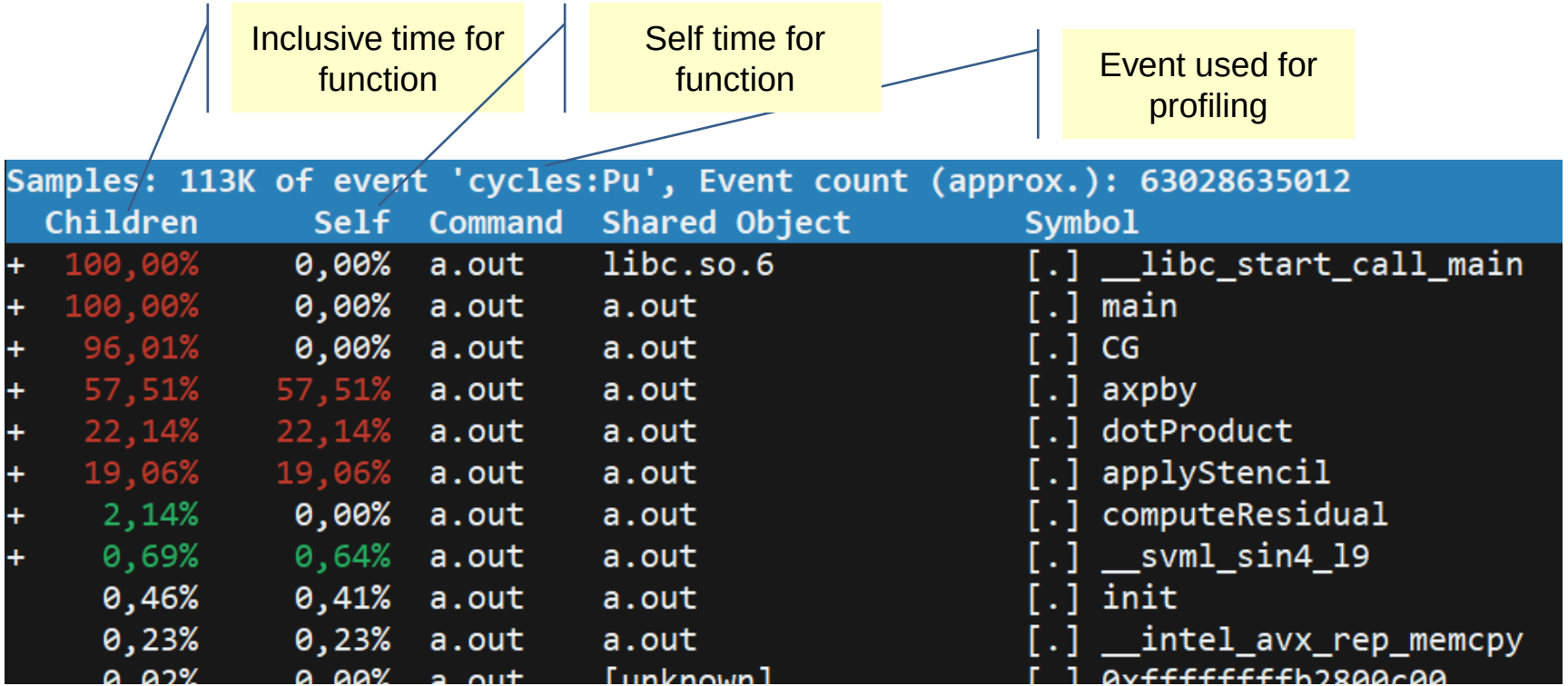
Analyze the results with:

```
$ perf report
```



```
Samples: 113K of event 'cycles:Pu', Event count (approx.): 63028635012
  Children      Self  Command  Shared Object          Symbol
+  100,00%     0,00%  a.out    libc.so.6              [.] __libc_start_call_main
+  100,00%     0,00%  a.out    a.out                  [.] main
+   96,01%     0,00%  a.out    a.out                  [.] CG
+   57,51%    57,51%  a.out    a.out                  [.] axpby
+   22,14%    22,14%  a.out    a.out                  [.] dotProduct
+   19,06%    19,06%  a.out    a.out                  [.] applyStencil
+    2,14%     0,00%  a.out    a.out                  [.] computeResidual
+    0,69%     0,64%  a.out    a.out                  [.] __svml_sin4_l9
     0,46%     0,41%  a.out    a.out                  [.] init
     0,23%     0,23%  a.out    a.out                  [.] __intel_avx_rep_memcpy
     0,02%     0,00%  a.out    [unknown]              [.] 0xffffffffb2800c00
```

Output of `perf report`



"profile browser" allows drilling into call tree if "`-g`" option was given for `perf record` (hit "h" for help)

Options for reporting with perf

- Show perf.data in an ncurses browser (TUI) if possible:
  ```
  $ perf report
  ```
- Show perf.data with a column for sample count:
  ```
  $ perf report -n
  ```
- Show perf.data as a text report, with data coalesced and percentages:
  ```
  $ perf report --stdio
  ```
- Disassemble and annotate instructions with percentages (needs some debuginfo):
  ```
  $ perf annotate --stdio
  ```

Some general remarks about profiling

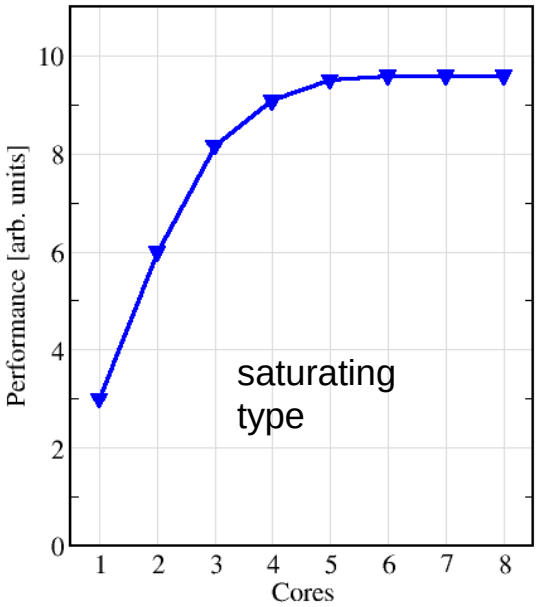
Manual profiling with a timer function

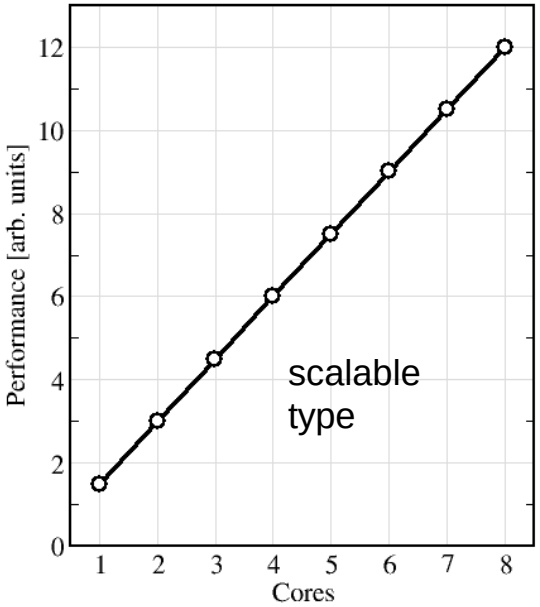
- Measuring walltime on UNIX (-like) systems
  - Stay away from CPU time – it's evil!
  - Use `clock_gettime()` to obtain wall-clock time stamp:

```
#include <time.h>

double getTimeStamp()
{
    struct timespec ts;
    clock_gettime(CLOCK_MONOTONIC, &ts);
    return (double)ts.tv_sec + (double)ts.tv_nsec * 1.e-9;
}

double gettimestamp_()
{
    return getTimeStamp();
}
```

Consequences from the saturation pattern for profiling

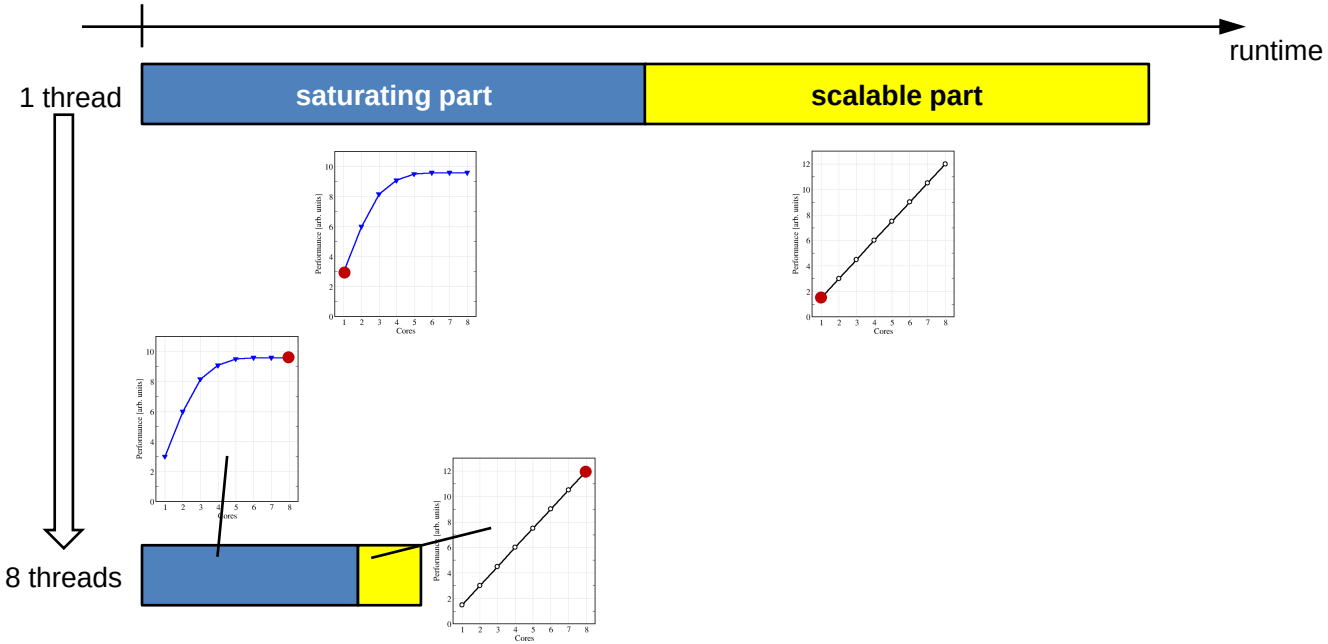
Clearly distinguish between “saturating” and “scalable” performance on the chip level





Consequences from the saturation pattern for profiling

- Some bottlenecks only show up in parallel execution!
- Code profile for single thread ≠ code profile for multiple threads
  - → Single-threaded profiling may be misleading



MPI program tracing with Intel Trace Analyzer/Collector (ITAC)

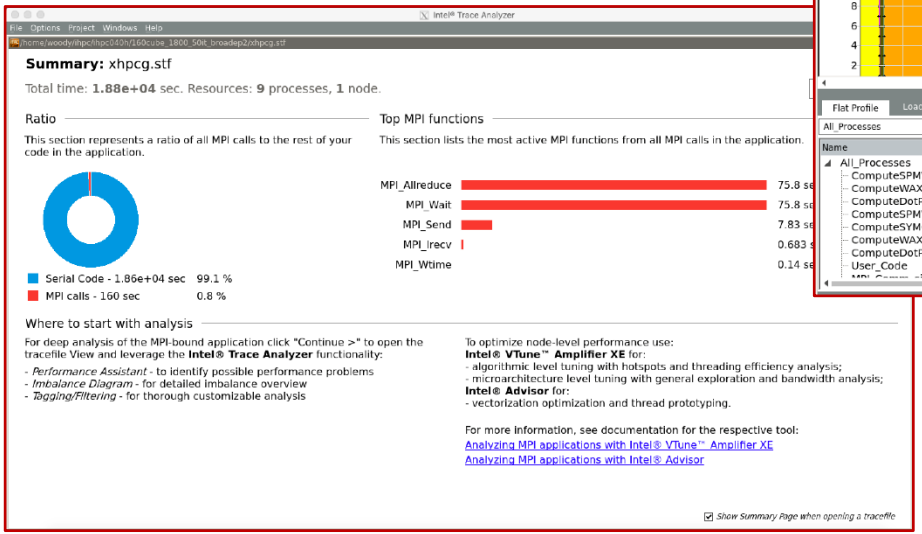
Georg Hager, Alireza Ghasemi, Ayesha Afzal

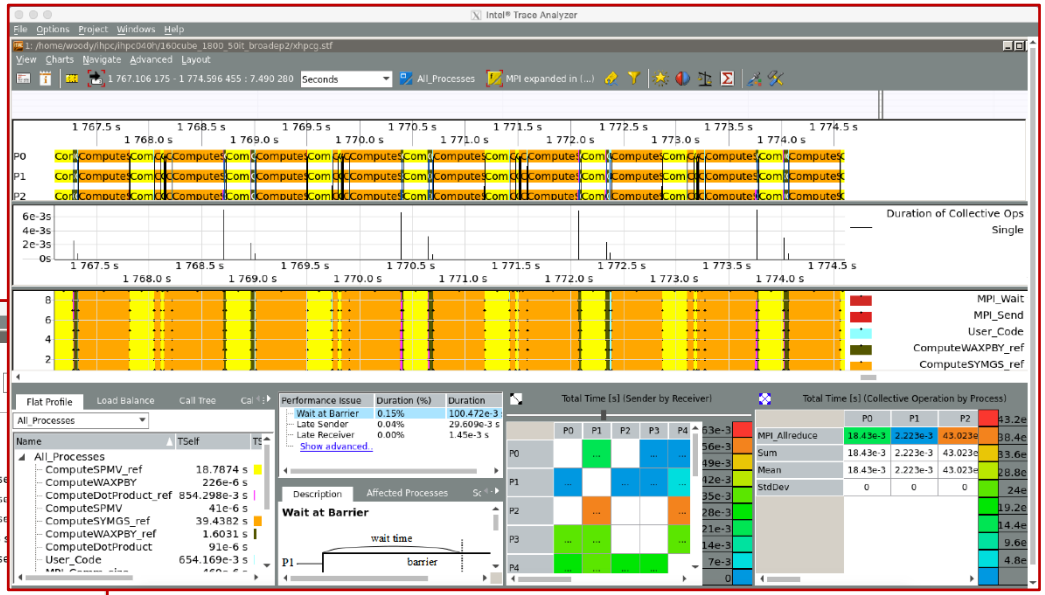
High Performance Computing

Intel Trace Anayzer and Collector

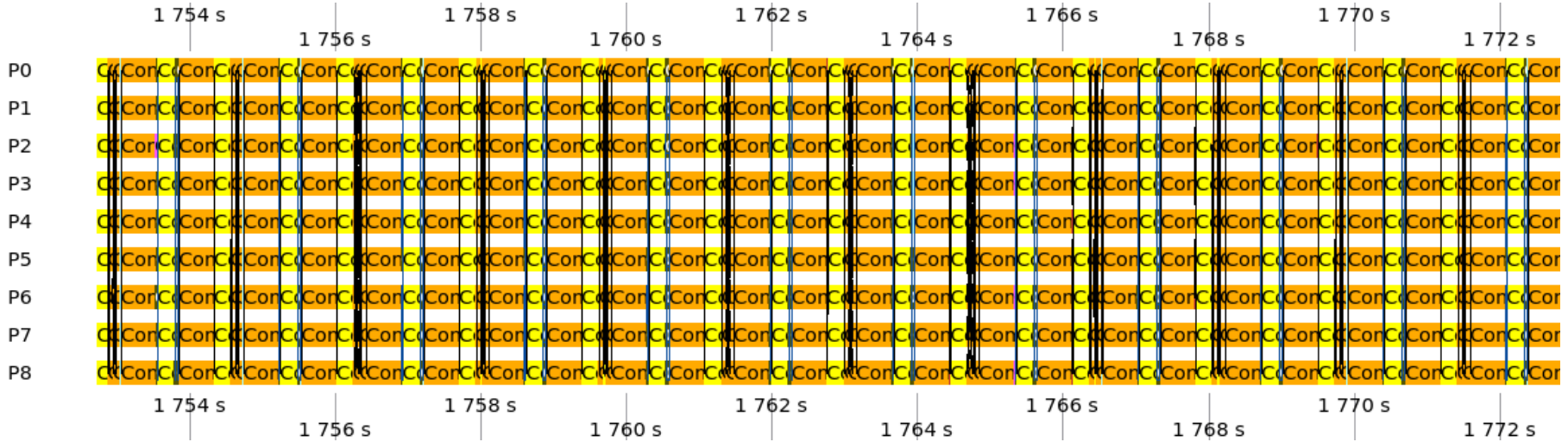
Event-based tool recording user function calls and MPI communication calls

GUI for advanced visualization



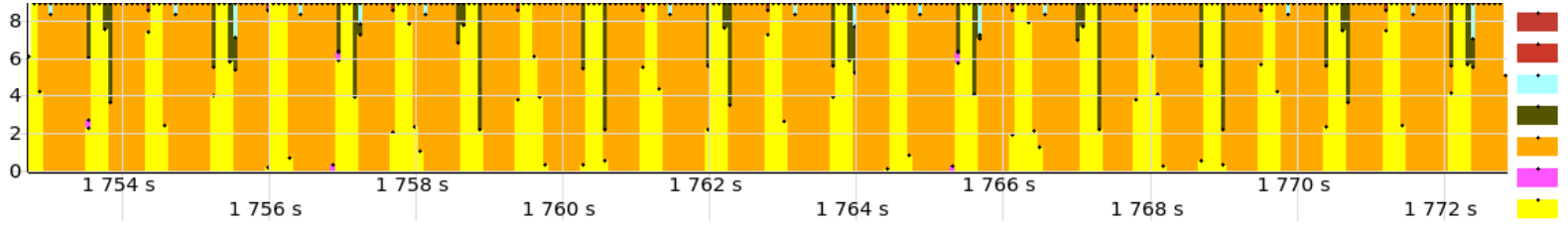


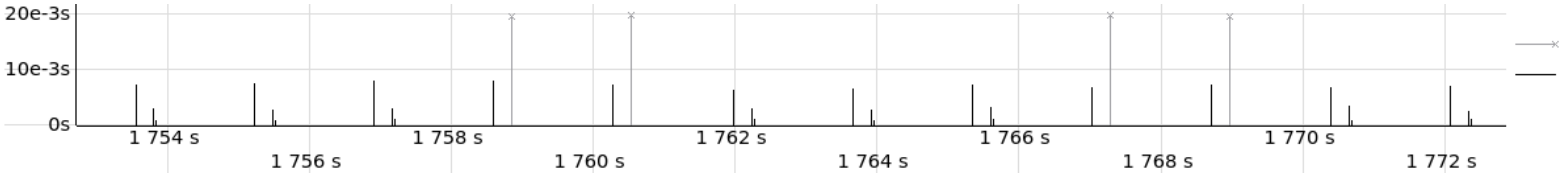
Event timeline view



- Timeline of MPI and user function execution
- Message visualization
- Context menu provides details on functions/messages
- Zoom/pan

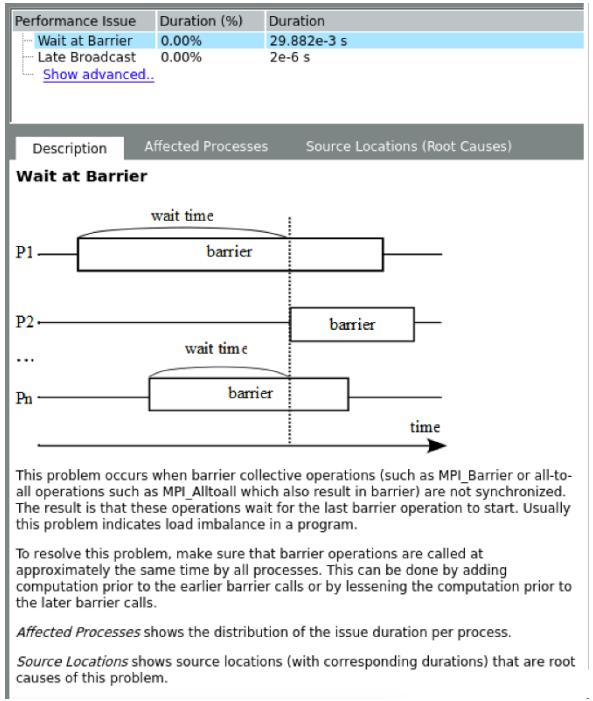
Quantitative and qualitative timelines

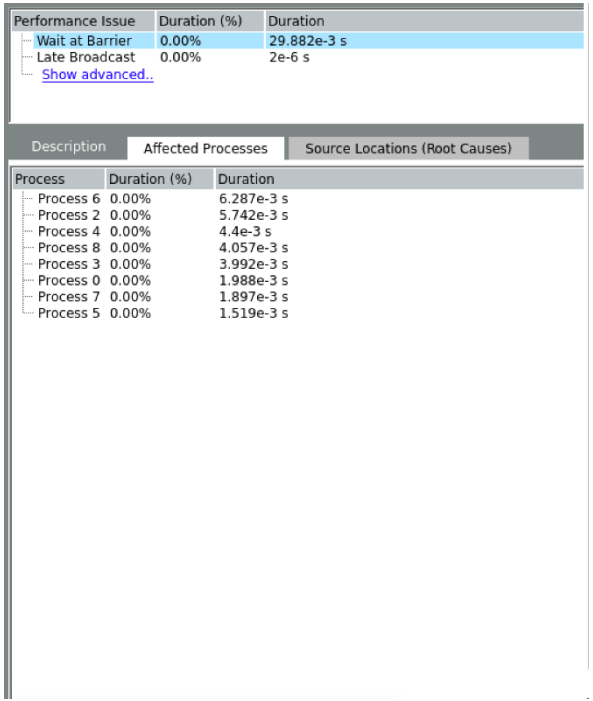




- Time spent in different MPI/user functions across processes
- Duration of certain things (collectives, PtP)

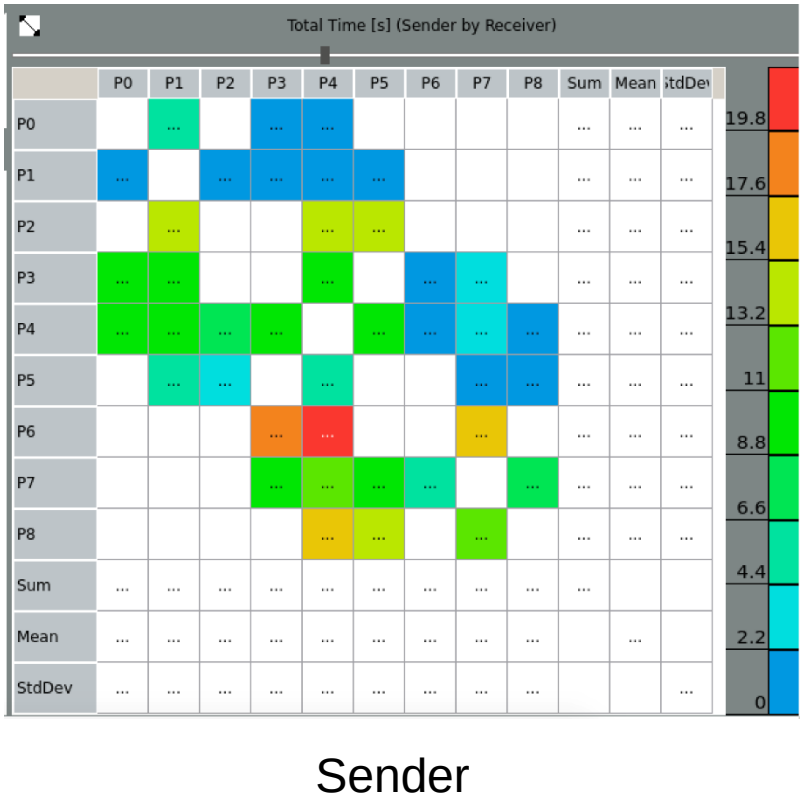
Performance advice





Context-sensitive advice on typical performance patterns

Message profile

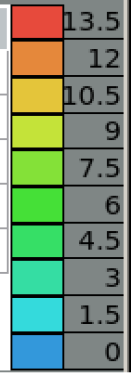


- Who sends how much to whom?
- How long does it take?
- Effective bandwidth?

Collective operations profile

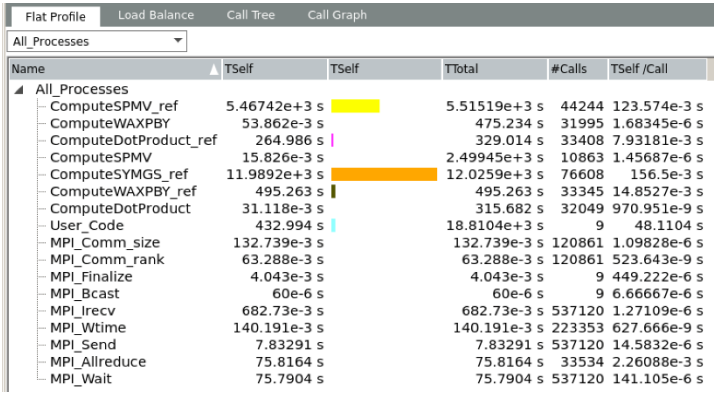
Total Time [s] (Collective Operation by Process)

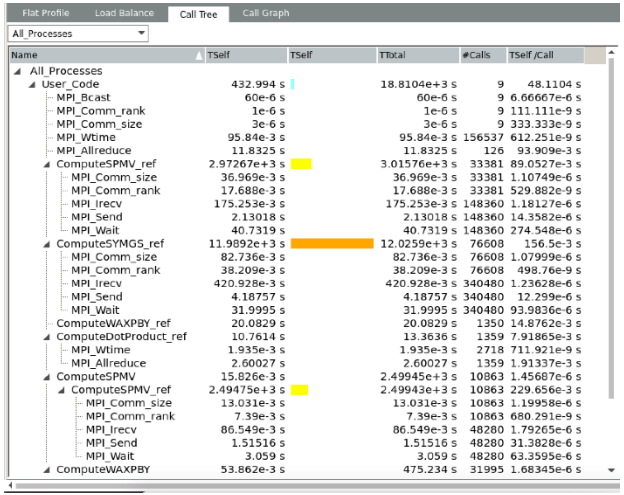
	P0	P1	P2	P3	P4	P5	P6	P7	P8	Sum	Mean	StdDev
MPI_Bcast	5e-6	7e-6	7e-6	7e-6	7e-6	7e-6	6e-6	7e-6	7e-6	60e-6	6.66667e-6	666.667e-9
MPI_Allreduce	6.98827	2.41008	14.1332	9.46671	9.80818	2.28141	12.1689	7.89127	10.6684	75.8164	8.42405	3.81376
Sum	6.98828	2.41009	14.1332	9.46671	9.80818	2.28142	12.1689	7.89127	10.6684	75.8165		
Mean	3.49414	1.20504	7.06659	4.73336	4.90409	1.14071	6.08444	3.94564	5.33422		4.21203	
StdDev	3.49413	1.20504	7.06658	4.73335	4.90409	1.1407	6.08444	3.94563	5.33422			5.00135

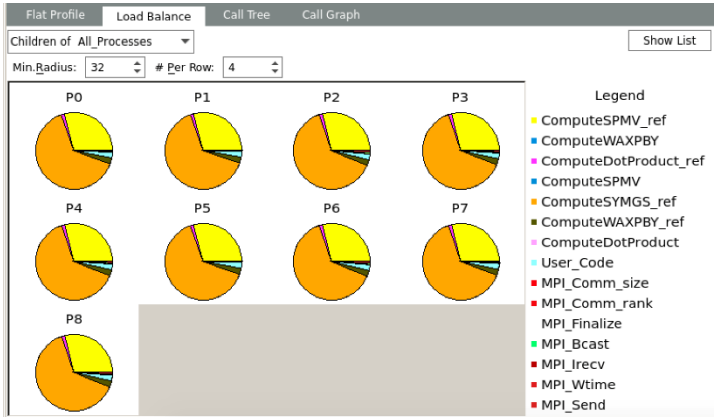


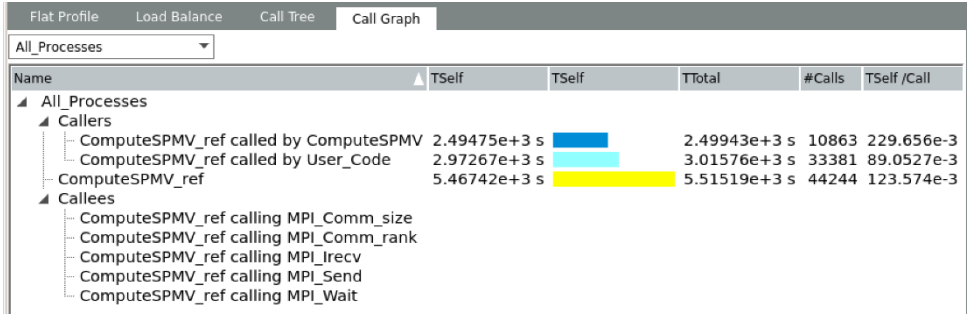
- Time spent in collective call
- Data volume sent/received

Functions profile, call tree/graph, load imbalance









Options for taking traces

- Caveat: Tracing can generate vast amounts of data!
- Compiler switches (only works with legacy Intel compiler and wrappers [mpiicc, mpiicpc, mpiifort])
  - `-trace` # record MPI calls (also possible with mpirun/mpiexec)
  - `-tcollect -trace` # record MPI and user code function calls
    # potential of large overhead and large trace size
  - `-tcollect-filter=func.txt -tcollect -trace` # filter file

func.txt example

```
'.*' OFF
'.*ComputeDotProduct.*' ON
'.*ComputeSYMGS.*' ON
'.*ComputeSPMV.*' ON
'.*ComputeWAXPBY.*' ON
```

More (important) configuration options

Environment variable	Default	Description
VT_FLUSH_PREFIX	... depends	control directly for temporary flush files
VT_LOGFILE_PREFIX	current working directory	control directly for physical trace information files
VT_LOGFILE_FORMAT	STF	`SINGLESTF`: rolls all trace files into one file (.single.stf)
VT_LOGFILE_NAME	${binary}.stf	control the name for the trace file
VT_MEM_BLOCKSIZE	64 KB	trace data in chunks of main memory
VT_MEM_FLUSHBLOCKS	1024	flushing is started when the number of blocks in memory exceeds this threshold
VT_MEM_MAXBLOCKS	1024	maximum number of blocks in main memory, if exceed the application is stopped until AUTOFLUSH/ MEM-OVERWRITE/ stop recording trace info
VT_CONFIG_RANK	0	control the process that reads and parses the configuration file

- Avoid rapid-fire dumping trace data into shared filesystems!
- Your fellow cluster users will hate you for it.

Alternatives

- ITAC is deprecated by Intel and will not be further developed (as of 2025)
  - Intel recommends VTune as a replacement, but this is not competitive

- Other tools with similar functionality
  - Vampir (commercial, scalable) https://vampir.eu/
  - Scalasca (for highly scalable programs, no trace view) https://www.scalasca.org/
  - Paraver https://tools.bsc.es/paraver

  - Jumpshot
    Don’t even bother.