Profiling using Performance Counters

Luca Tornatore, I.N.A.F.

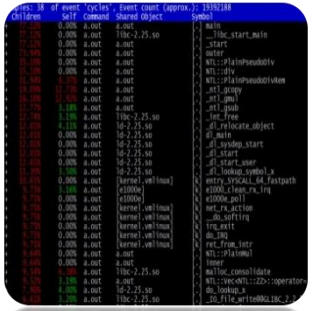
2025 INAF Course on HPC

September, 22nd - 26th, OACT, Catania

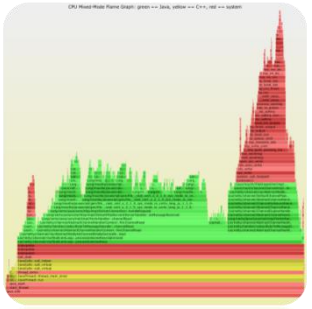
Outline

PMUs

What is **perf**

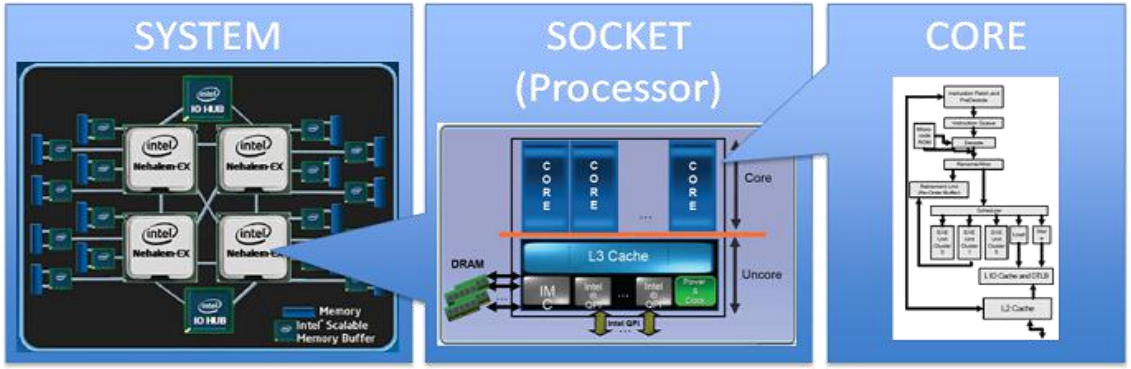


Using **perf**



Profiling with **perf**

How well does the CPU work ?

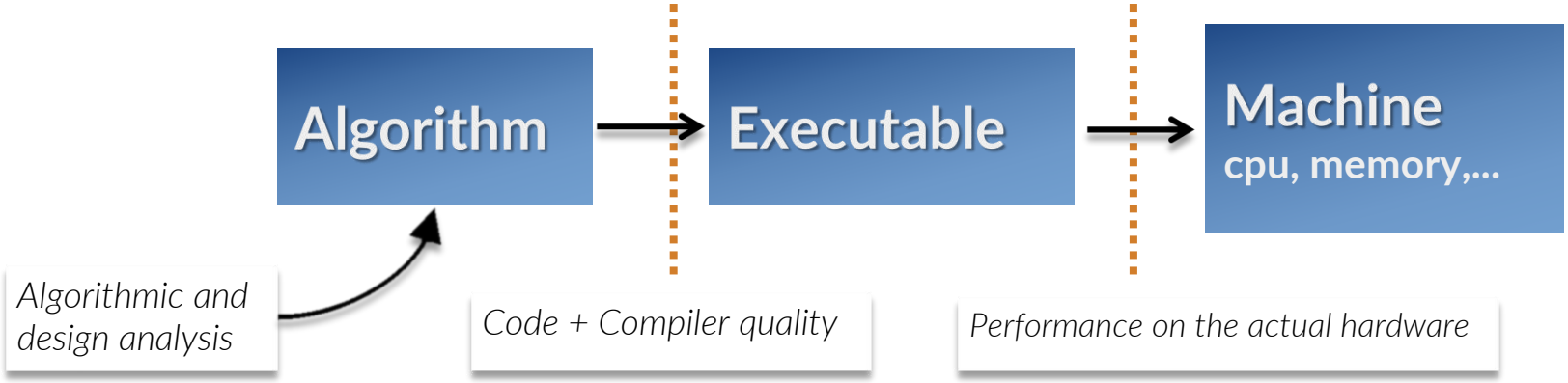


The **CPU utilization** number – the figure that the *NIX "top" utility reports – is the **fraction of time slots that the CPU scheduler in the OS assigned to execution** of running programs or the OS itself.

For **compute-bound workloads,** this figure predicted the remaining CPU capacity fairly well for architectures of 80ies and early 90ies.

This metric is now unreliable because of introduction of multi core and multi CPU systems, multi-level caches, non-uniform memory, simultaneous multithreading (SMT), pipelining, out-of-order execution.

Who makes the CPU working well?

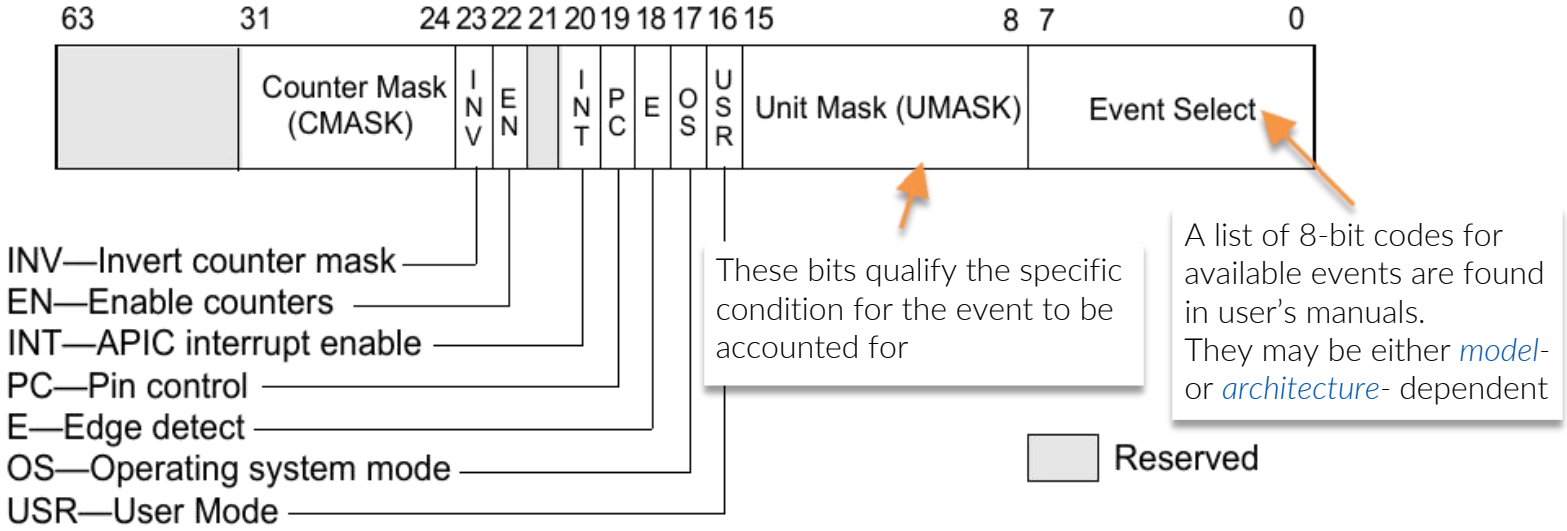


Modern high-end **processors** provide **on-chip hardware** that monitors processor's performance and inside events.

That allows to obtain a "precise" and dynamic picture of CPU resources utilization.

These data can guide performance improvement efforts

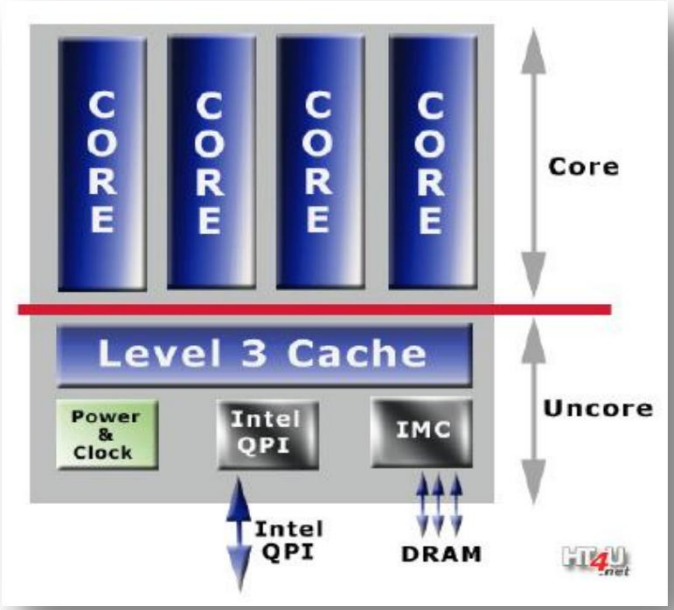
Performance Monitoring Units



The PMU consists of two types of registers:

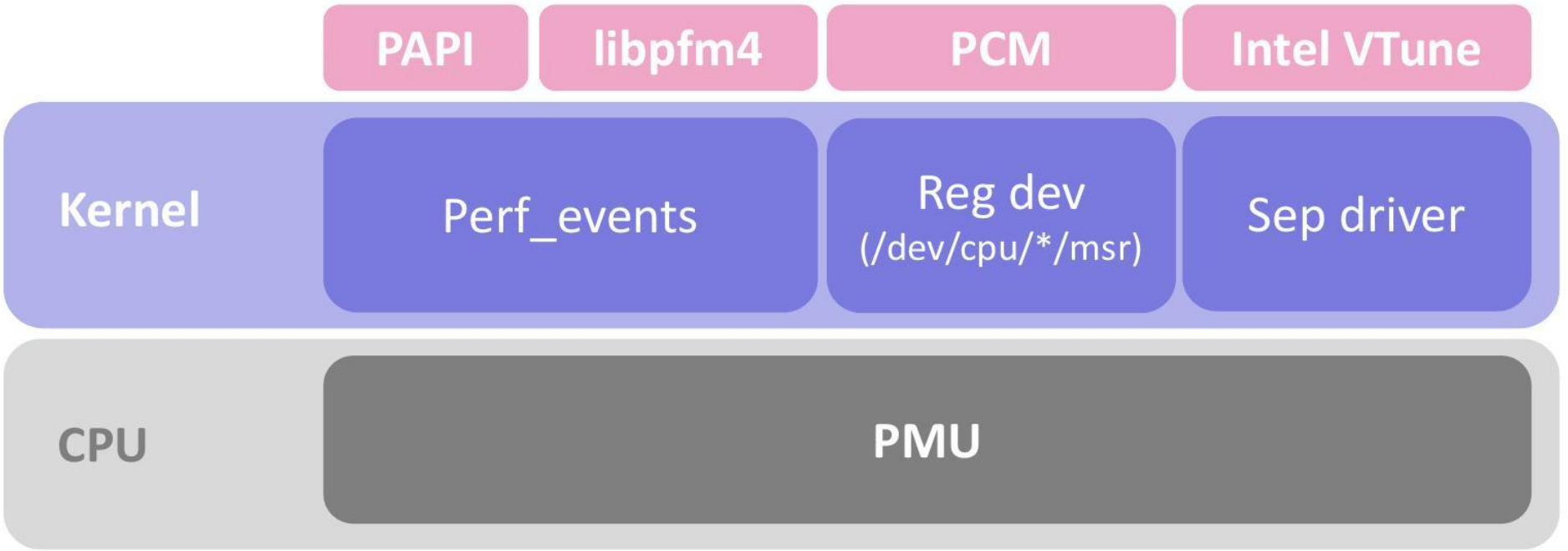
- Performance Event Select Register
- Performance Monitor Counter

Type of intel counters

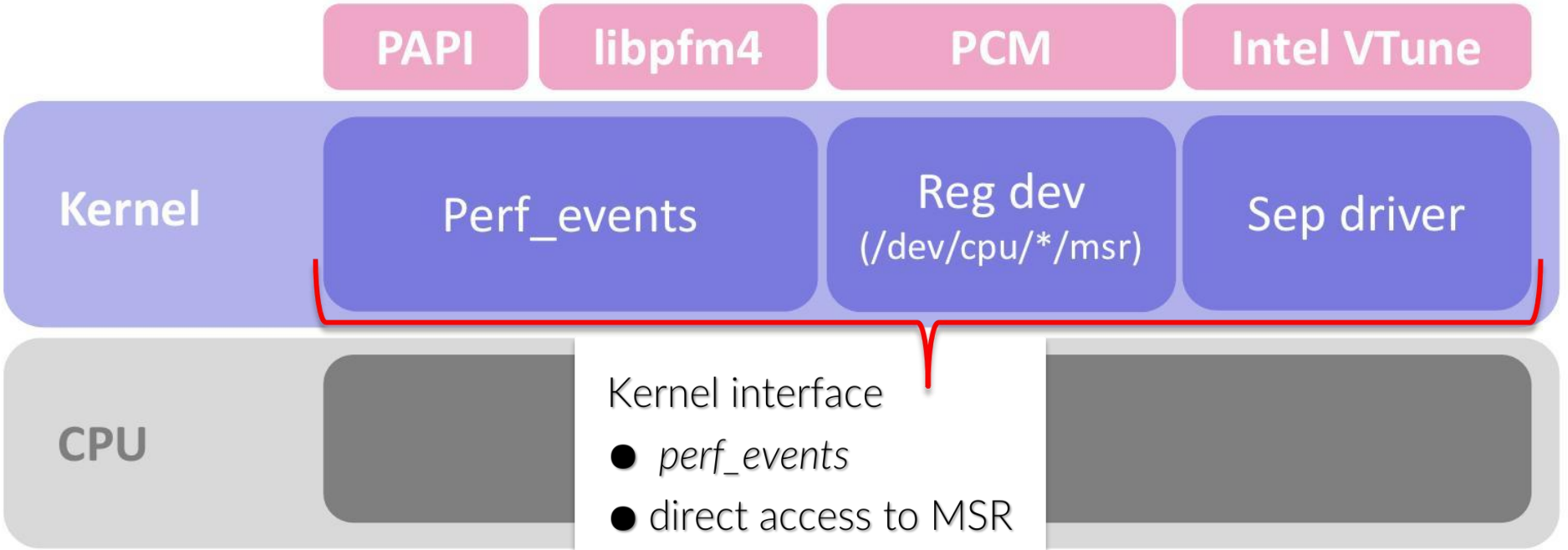


- **Fixed function counters**
  - Predefined events that are commonly used
  - TSC, instructions retired, core clock cycles, …
- **General purpose performance counters**
  - can be programmed to follow a specific event
- **Precise Event-Based Sampling (PEBS)**
  - Can keep track of architectural state right after instruction causes event
  - Can trigger interrupt (PMI) coupled to counter

Accessing the counters



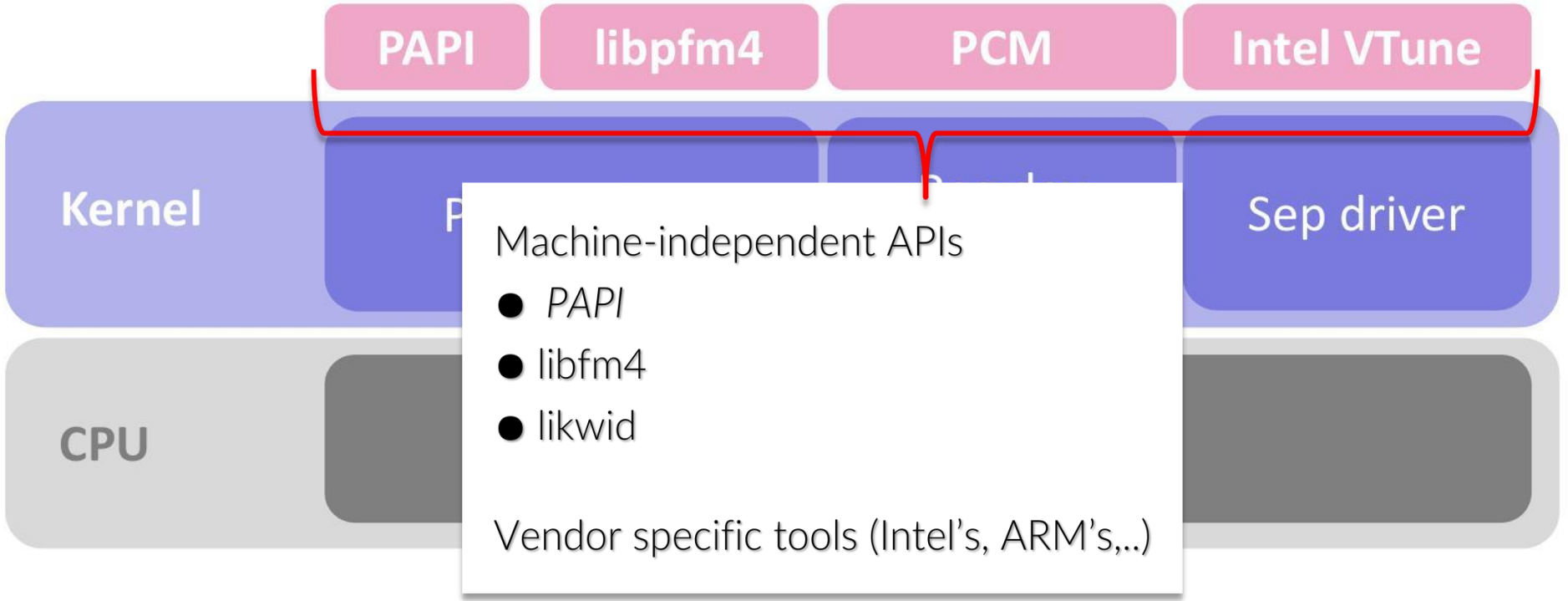
Accessing the counters



Kernel interface

- *perf_events*
- direct access to MSR
- dedicated drivers

Accessing the counters



Machine-independent APIs

- *PAPI*
- libfm4
- likwid

Vendor specific tools (Intel's, ARM's,..)

Accessing the counters

Direct acces to fixed-function perf. count. through `rdpmc`

Using `PERF`, `PAPI`, `PCM`, `LIKWID`, ..., is definitely easier

```
// rdpmc_instructions uses a "fixed-function" performance counter to return the count
//       the current core in the low-order 48 bits of an unsigned 64-bit integer.
unsigned long rdpmc_instructions()
{
   unsigned a, d, c;

   c = (1<<30);
   __asm__ volatile("rdpmc" : "=a" (a), "=d" (d) : "c" (c));

   return ((unsigned long)a) | (((unsigned long)d) << 32);;
}

// rdpmc_actual_cycles uses a "fixed-function" performance counter to return the coun
//       executed by the current core.  Core cycles are not accumulated while the pro
//       which is used when the operating system has no task(s) to run on a processor
unsigned long rdpmc_actual_cycles()
{
   unsigned a, d, c;

   c = (1<<30)+1;
   __asm__ volatile("rdpmc" : "=a" (a), "=d" (d) : "c" (c));

   return ((unsigned long)a) | (((unsigned long)d) << 32);;
}

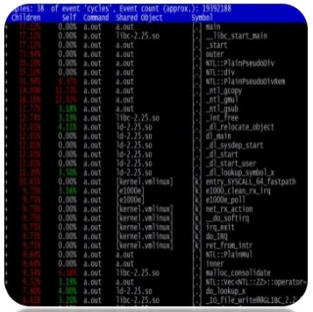
// rdpmc_reference_cycles uses a "fixed-function" performance counter to return the c
//       CPU core cycles executed by the current core.  This counts at the same rate
//       when the core is in the "HALT" state.  If a timed section of code shows a la
//       rdpmc_reference_cycles, the processor probably spent some time in a HALT sta
unsigned long rdpmc_reference_cycles()
{
   unsigned a, d, c;

   c = (1<<30)+2;
   __asm__ volatile("rdpmc" : "=a" (a), "=d" (d) : "c" (c));

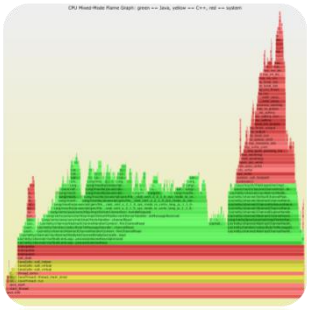
   return ((unsigned long)a) | (((unsigned long)d) << 32);;
}
```

Outline

What is **perf**



Using **perf**



Profiling with **perf**

What is perf ?

PERF – Performance Events for Linux – is the standard profiling infrastructure on Linux, built in the kernel since version 2.6.

It strips away the CPUs hardware differences among different systems and presents an abstracted unique command-line interface for performance measurements.

PERF is the standard way to access the hardware performance counters, in both sampling and counting mode.

It consists of:

- a kernel SYSCALL that provide access to both system-software and hardware events;
- a collection of user-space tools to collect, display and analyze performance data.

References:

- https://perf.wiki.kernel.org/index.php/Tutorial
- http://brendangregg.com/perf.html

must-read advice

Using `perf` requires either to have `root` privileges or to lower the access protection at kernel level.
That is because perf allows you to spy intimate details of what happens on your machine and as suche may be used for malicious purposes.
The best solution is to enable the users to access the perf events temporarly only when you need it, so that it is not a permanent setting in your kernel.

You achieve this goal by opening a shell and typing

```
sudo echo 0 > /proc/sys/kernel/kptr_restrict
sudo echo -1 > /proc/sys/kernel/perf_event_paranoid
```

A handy solution is to put the two above lines

```
echo 0 > /proc/sys/kernel/kptr_restrict
echo -1 > /proc/sys/kernel/perf_event_paranoid
```

into a text file, for instance named `enable_perf` in any path `path/to/script` you prefer, making it executable with `mod +x enable_perf` and then execute it from a shell as `sudo`

```
sudo path/to/script/enable_perf
```

Hello `perf`

```
luca@GGG:~% perf

 usage: perf [--version] [--help] [OPTIONS] COMMAND [ARGS]

 The most commonly used perf commands are:
   annotate        Read perf.data (created by perf record) and display annotated code
   archive         Create archive with object files with build-ids found in perf.data file
   bench           General framework for benchmark suites
   buildid-cache   Manage build-id cache.
   buildid-list    List the buildids in a perf.data file
   c2c             Shared Data C2C/HITM Analyzer.
   config          Get and set variables in a configuration file.
   data            Data file related processing
   diff            Read perf.data files and display the differential profile
   evlist          List the event names in a perf.data file
   ftrace          simple wrapper for kernel's ftrace functionality
   inject          Filter to augment the events stream with additional information
   kallsyms        Searches running kernel for symbols
   kmem            Tool to trace/measure kernel memory properties
   kvm             Tool to trace/measure kvm guest os
   list            List all symbolic event types
   lock            Analyze lock events
   mem             Profile memory accesses
   record          Run a command and record its profile into perf.data
   report          Read perf.data (created by perf record) and display the profile
   sched           Tool to trace/measure scheduler properties (latencies)
   script          Read perf.data (created by perf record) and display trace output
   stat            Run a command and gather performance counter statistics
   test            Runs sanity tests.
   timechart       Tool to visualize total system behavior during a workload
   top             System profiling tool.
   probe           Define new dynamic tracepoints
   trace           strace inspired tool
```

Hello `perf`

```
luca@GGG:~% perf

 usage: perf [--version] [--help] [OPTIONS] COMMAND [ARGS]

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Note: to obtain the list of options for each command use

`perf` *`command`* `-h`

TYPE OF EVENTS

The kernel interface can measure and report events from several different sources:

- **software events :** pure software events (ex: context switches)
- **PMU hardware events :** Performance Monitoring Unit (PMU) microarchitectural events (ex. Nr. of instructions retired, branch-misses, …)
- **hardware events :** common hardware events with mnemonic names, mapped on actual CPU events
- **tracepoint events :** implemented through the kernel *ftrace* infrastracture.

HOW MANY EVENTS IN YOUR CPU ?

Let's have a look:

- `perf list`
- `showevtinfo  [ pmu-tools ]`
- `papi_avail  [ PAPI ]`
- `likwid-perfctr -e`
- https://download.01.org/perfmon/

...hundreds of different events

Names for perf Events

Some commonly used events have mnemonic names:

```
List of pre-defined events (to be used in -e):

  branch-instructions OR branches                    [Hardware event]
  branch-misses                                      [Hardware event]
  bus-cycles                                         [Hardware event]
  cache-misses                                       [Hardware event]
  cache-references                                   [Hardware event]
  cpu-cycles OR cycles                               [Hardware event]
  instructions                                       [Hardware event]
  ref-cycles                                         [Hardware event]

  alignment-faults                                   [Software event]
  bpf-output                                         [Software event]
  context-switches OR cs                             [Software event]
  cpu-clock                                          [Software event]
  cpu-migrations OR migrations                       [Software event]
  dummy                                              [Software event]
  emulation-faults                                   [Software event]
  major-faults                                       [Software event]
  minor-faults                                       [Software event]
  page-faults OR faults                              [Software event]
  task-clock                                         [Software event]

  L1-dcache-load-misses                              [Hardware cache event]
  L1-dcache-loads                                    [Hardware cache event]
  L1-dcache-stores                                   [Hardware cache event]
  L1-icache-load-misses                              [Hardware cache event]
  LLC-load-misses                                    [Hardware cache event]
  LLC-loads                                          [Hardware cache event]
  LLC-store-misses                                   [Hardware cache event]
  LLC-stores                                         [Hardware cache event]
  branch-load-misses                                 [Hardware cache event]
  branch-loads                                       [Hardware cache event]
  dTLB-load-misses                                   [Hardware cache event]
  dTLB-loads                                         [Hardware cache event]
  dTLB-store-misses                                  [Hardware cache event]
  dTLB-stores                                        [Hardware cache event]
```

perf Events

An event can also be specified by its processor-specific identifier, that usually is a hex value

Example:

```
"EventCode": "0x00",
   "UMask": "0x01",
   "EventName": "INST_RETIRED.ANY",
   "BriefDescription": "Instructions retired from execution.“

"EventCode": "0x00",
   "UMask": "0x02",
   "EventName": "CPU_CLK_UNHALTED.THREAD",
   "BriefDescription": "Core cycles when the thread is not in halt state"
```

perf Events

You can specify events by their raw code if not present in **perf list**

```
perf stat -e r5100c0 …
```

You may obtain the hex code in several way

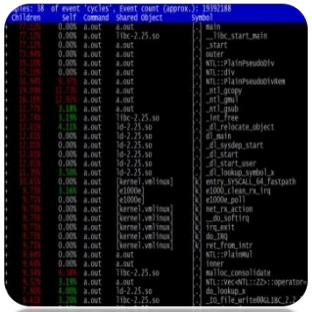
1. Look in the list provided by Intel, combining “Umask” and “Event Code” fields

```
perf stat -e r<umask><eventselector>  …
perf stat -e cpu/event=0xcode,umask=0xcode/u  …
```

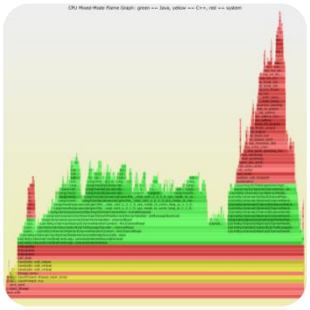
1. Use **libpfm4**, using **showevtinfo** and then **check_events**:

```
check_events <event name>:<umask>[(:modifers)*]
```

Outline



Using
perf



Profiling
with perf

Right answers to right questions

- Which code segments take most of the execution time ?
  What are the causes ? *(cache misses, branch misses, non-optimal pipelines..)*
- Do the performance counters suggest something about performance issues ?
- Do the performance counters offer some hints on how to fix the issues?

Workflow:

1. Run the program and collect as many data as possible
2. Analyse the collected data and profile the program

Right answers to right questions

EVENT–based profiling

can be accessed from inside the code

collecting precise values of events counters in a given time range

SAMPLE–based profiling

periodic sampling of program/system status and of event counters values

Right answers to right questions

EVENT–based profiling

can be accessed from inside the code

collecting precise values of events counters in a given time range

Counting events with `perf`

For all supported events, `perf stat` can count during a process execution:

```
luca@GGG:~% perf stat -B dd if=/dev/zero of=/dev/null count=1000000
1000000+0 records in
1000000+0 records out
512000000 bytes (512 MB, 488 MiB) copied, 1.0796 s, 474 MB/s

 Performance counter stats for 'dd if=/dev/zero of=/dev/null count=1000000':

       1078.764601      task-clock (msec)         #    0.997 CPUs utilized
                 9      context-switches          #    0.008 K/sec
                 1      cpu-migrations            #    0.001 K/sec
                74      page-faults               #    0.069 K/sec
     2,152,108,887      cycles                    #    1.995 GHz
     1,986,849,204      instructions              #    0.92  insn per cycle
       387,532,518      branches                  #  359.237 M/sec
         8,022,754      branch-misses             #    2.07% of all branches

       1.081948899 seconds time elapsed
```

Counting events with perf

You can specify the events you want to profile by their mnemonic names:

```
perf stat -e cycles:.,instructions:.,branch-misses:.,cache-misses:.
```

If you specify more events than available counters, the kernel uses time multiplexing to sample all the events; then perf scales the count based on running time vs the total amount of time that a given event has been active

```
final_count = raw_count * time_enabled / time_runnig
```

Counting events with perf

Processor-wide mode:

```
perf stat -e cycles:u -a ./executable arguments
```

Sampling a subset of cores:

```
perf stat -e cycles:u -a -C 1,4-5 ./executable arguments
```

Profile a given process:

```
perf stat -e cycles:u -p PID sleep 2
```

Pretty printing of large numbers

```
perf stat -B -e cycles:u -e instructions:u -e branch-misses:u ./executable arguments
```

Repeat and average measures

```
perf stat -r 10 -B -e cycles:u -e instructions:u ./executable arguments
```

Right answers to right questions

SAMPLE–based data collection

periodic sampling of program/system
status and of event counters values


Collecting information with `perf`

You can collect much more information, with line-level detail:

```
perf record -e cycles:.,instructions:.,branch-misses:.,cache-misses:.
```

A file named `perf.data` will be produced, with all the data collected during the `perf` activity.

At odds with `perf stat`, this mode profiles CPU usage based on sampling the instruction pointer or stack tree at a given rate:

```
perf record -F fff -a -k CLOCK_MONOTONIC -- sleep 10
```

Sample the whole systems (`-a`, all CPUs) at fff Hertz (`-F fff`) without accounting for the perf activity (`--`) for 10 secs.

Sampling the call stack

You can collect dynamic information about the call-stack (so that to obtain the call graph)

```
perf record --call-graph <record_mode [,record_size ]>
```

Where `record_mode` can be `<fp|dwarf|lbr>` and `record_size` is the max size of stack recording (in bytes) for `dwarf` mode (def: 8192)

You can specify `-a` (all CPUs) ; `-C, --cpu <cpu>` ; `-s, --per-thread` ;

Now, let's go back to our friend lie.c to check whether `perf` is mislead as much as `gprof` was…


Sampling the call stack

```
perf report --call-graph graph,0.6,100,caller --stdio --no-children
```

```
# Total Lost Samples: 0
#
# Samples: 740  of event 'cycles:ppp'
# Event count (approx.): 556806058
#
# Overhead  Command  Shared Object      Symbol
# ........  .......  .................  ...........
#
    99.61%  lie1.g   lie1.g             [.] loop
            |
            ---_start
               __libc_start_main
               main
               |
               |--98.73%--heavy
               |          loop
               |
                --0.88%--light
                          loop
```

caller order

```
# Total Lost Samples: 0
#
# Samples: 740  of event 'cycles:ppp'
# Event count (approx.): 556806058
#
# Overhead  Command  Shared Object      Symbol
# ........  .......  .................  ...........
#
    99.61%  lie1.g   lie1.g             [.] loop
            |
            ---loop
               |
               |--98.73%--heavy
               |          main
               |          __libc_start_main
               |          _start
               |
                --0.88%--light
                          main
                          __libc_start_main
```

callee order


Collecting information with `perf`

As well, you can record performance events along with the call stack

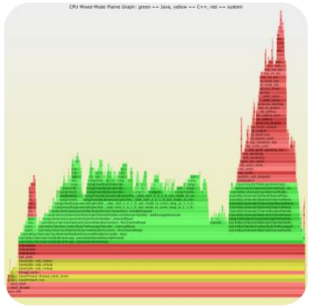
```
perf record --call-graph … -e event_1:.,event_2:.,event_3:. …
```

With all the same options valid before.
Check `perf record -h` for more details.

Note:

remember to compile (with **`gcc`**) with
`-fno-omit-frame-pointer`
in order to reconstruct the call stack

Outline



Profiling with **perf**

Recovering the call stack

Once you have **perf.data** file, you can easily get the call graph

```
perf report -call-graph --stdio
```

```
# Samples: 52K of event 'cycles:.pppu'
# Event count (approx.): 32241477547
#
# Children      Self  Command          Shared Object       Symbol
# ........  ........  ...............  ..................  ......................
#
   100.00%     0.00%  prefetching_on.  prefetching_on.03   [.] _start
           |
           ---_start
              __libc_start_main
              main
              |
               --0.68%--rand
                         __random

   100.00%     0.00%  prefetching_on.  libc-2.27.so        [.] __libc_start_main
           |
           ---__libc_start_main
              main
              |
               --0.68%--rand
                         __random

   100.00%    98.82%  prefetching_on.  prefetching_on.03   [.] main
           |
           |--98.82%--_start
           |          __libc_start_main
           |          main
           |
            --1.18%--main
                      |
                       --0.68%--rand
                                 __random

     0.72%     0.08%  prefetching_on.  libc-2.27.so        [.] rand
           |
            --0.64%--rand
                      __random

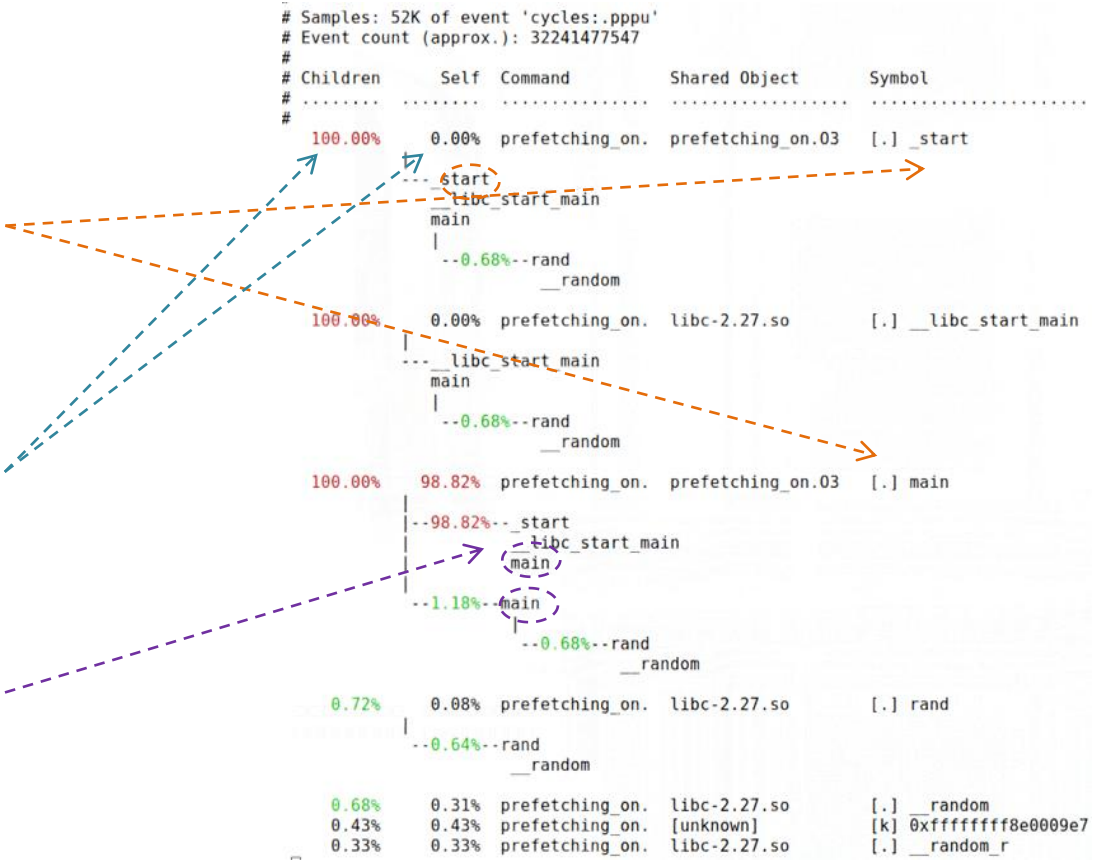
     0.68%     0.31%  prefetching_on.  libc-2.27.so        [.] __random
     0.43%     0.43%  prefetching_on.  [unknown]           [k] 0xffffffff8e0009e7
     0.33%     0.33%  prefetching_on.  libc-2.27.so        [.] __random_r
```

Recovering the call stack

The symbol this call refers to

Children time and self time are reported separately

Both *caller* and *callee* informations



Recovering the call stack

```
perf report -call-graph -stdio \
--no-children
```

```
# Samples: 52K of event 'cycles:.pppu'
# Event count (approx.): 32241477547
#
# Overhead  Command          Shared Object      Symbol
# ........  ...............  .................  ........................
#
    98.82%  prefetching_on.  prefetching_on.03  [.] main
            |
             --98.81%--main
                       __libc_start_main
                       _start

     0.43%  prefetching_on.  [unknown]          [k] 0xffffffff8e0009e7
     0.33%  prefetching_on.  libc-2.27.so       [.] __random_r
     0.31%  prefetching_on.  libc-2.27.so       [.] __random
     0.08%  prefetching_on.  libc-2.27.so       [.] rand
     0.03%  prefetching_on.  prefetching_on.03  [.] rand@plt
     0.00%  prefetching_on.  libc-2.27.so       [.] _dl_addr
     0.00%  prefetching_on.  ld-2.27.so         [.] _dl_relocate_object
     0.00%  prefetching_on.  ld-2.27.so         [.] do_lookup_x
     0.00%  prefetching_on.  ld-2.27.so         [.] strcmp
     0.00%  prefetching_on.  ld-2.27.so         [.] __GI___tunables_init
```

Recovering the call stack

```
perf report -call-graph -stdio \
--no-children
```

callee format as default

```
# Samples: 52K of event 'cycles:.pppu'
# Event count (approx.): 32241477547
#
# Overhead  Command          Shared Object      Symbol
# ........  ...............  .................  ........................
#
    98.82%  prefetching_on.  prefetching_on.03  [.] main
            |
             --98.81%--main
                       __libc_start_main
                       _start

     0.43%  prefetching_on.  [unknown]          [k] 0xffffffff8e0009e7
     0.33%  prefetching_on.  libc-2.27.so       [.] __random_r
     0.31%  prefetching_on.  libc-2.27.so       [.] __random
     0.08%  prefetching_on.  libc-2.27.so       [.] rand
     0.03%  prefetching_on.  prefetching_on.03  [.] rand@plt
     0.00%  prefetching_on.  libc-2.27.so       [.] _dl_addr
     0.00%  prefetching_on.  ld-2.27.so         [.] _dl_relocate_object
     0.00%  prefetching_on.  ld-2.27.so         [.] do_lookup_x
     0.00%  prefetching_on.  ld-2.27.so         [.] strcmp
     0.00%  prefetching_on.  ld-2.27.so         [.] __GI___tunables_init
```

Recovering the call stack

```
perf report --call-graph --stdio \
--no-children --sort=dso
```

Different ordering are possible:
comm, dso, symbol,...

```
# Samples: 52K of event 'cycles:.pppu'
# Event count (approx.): 32241477547
#
# Overhead  Shared Object
# ........  ..................
#
    98.84%  prefetching_on.03
            |
            ---_start
               __libc_start_main
               main

     0.72%  libc-2.27.so
            |
            ---_start
               __libc_start_main
               main
               |
                --0.68%--rand
                          __random

     0.43%  [unknown]
```

Recovering the call stack

```
perf report --call-graph --stdio \
--no-children --sort=comm
```

Different ordering are possible:
comm, dso, symbol,...

```
# Samples: 52K of event 'cycles:.pppu'
# Event count (approx.): 32241477547
#
# Overhead  Command
# ........  ...............
#
   100.00%  prefetching_on.
            |
             --100.00%--_start
                        __libc_start_main
                        main
                        |
                         --0.68%--rand
                                   __random
```

Recovering the call stack

```
perf report --call-graph --stdio \
--no-children
```

The graph for all the events recorderd are shown

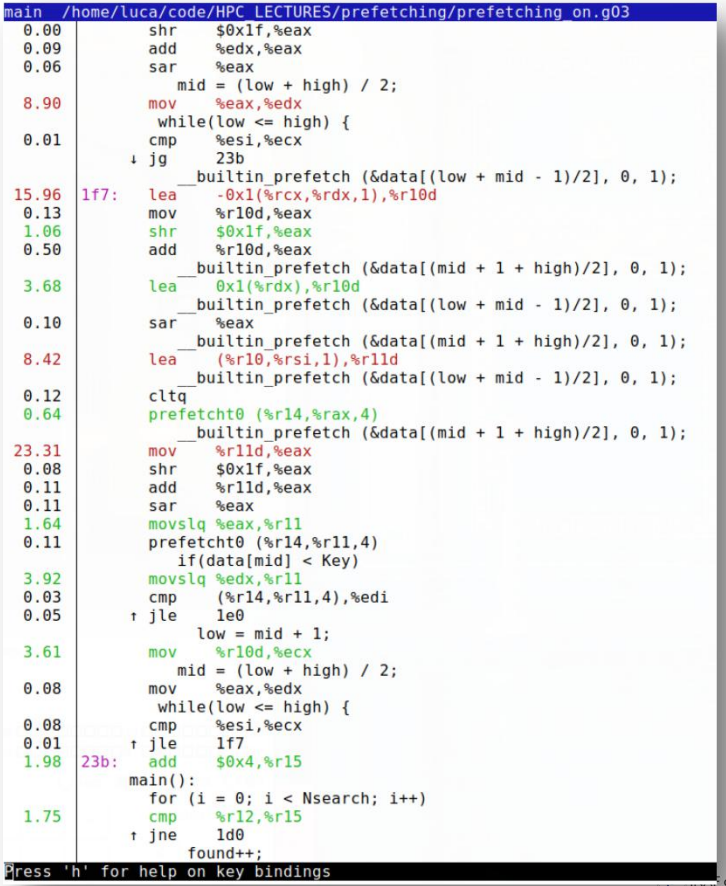
```
# Samples: 55K of event 'instructions:.u'
# Event count (approx.): 9679409860
#
# Overhead  Command          Shared Object      Symbol
# ........  ...............  .................  ..............
#
    97.01%  prefetching_on.  prefetching_on.03  [.] main
            |
            ---_start
               __libc_start_main
               main

     2.05%  prefetching_on.  libc-2.27.so       [.] __random
            |
            ---_start
               __libc_start_main
               main
               rand
               __random
```

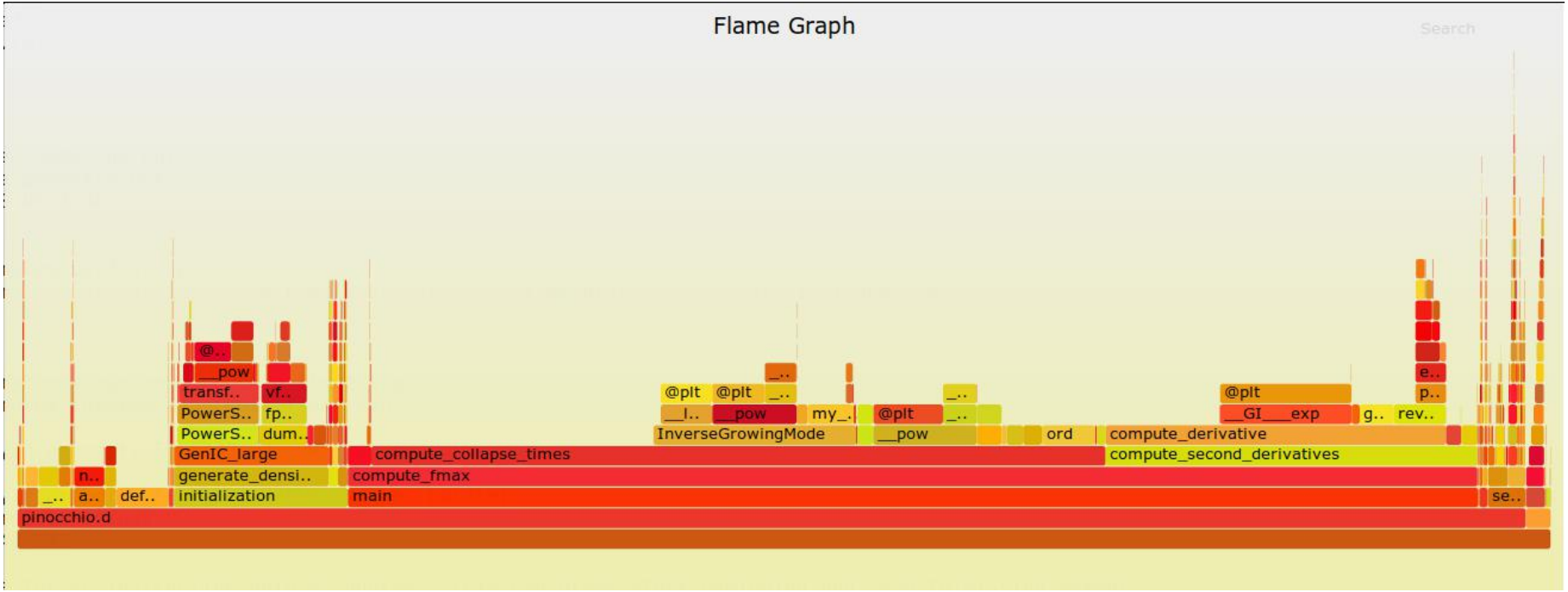
Detailed browsing of the events

You can browse your code at line-level detail, with reported metrics for all the events that you requested

→ *see live examples*

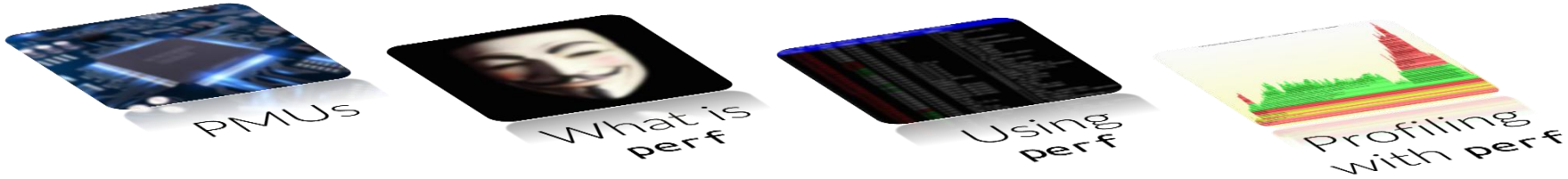


Flame graphs



Have a look at Brend Gregg's blog: http://www.brendangregg.com/FlameGraphs/cpuflamegraphs.html

Outline



Addendum I

Elementary intro to PAPI

(very) Basic usage of PAPI

INITIALIZATION

- define events you want to profile
- reserve room for counter values
- initialize library
- program each event separately

```c
#include "papi.h"

#define PCHECK(e) \
  if (e!=PAPI_OK)                                          \
    {printf("Problem in papi call, line %d\n",__LINE__); return 1;}

#define NEVENTS 3

int main(int argc, char **argv)
{
  int events[NEVENTS] =
    {
      PAPI_TOT_CYC,/* total cycles */
      PAPI_L1_DCM, /* stalls on L1 cache miss */
      PAPI_L2_DCM, /* stalls on L2 cache miss */
    };

  long_long             values[NEVENTS];
  int                   retval;


  retval = PAPI_library_init(PAPI_VER_CURRENT);
  if (retval != PAPI_VER_CURRENT)
    printf("wrong PAPI initialization: %d instead of %d\n", retval, PAPI_VER_CURRENT);

  {
    for ( int i = 0; i < NEVENTS; i++ )
      {
        retval = PAPI_query_event(events[i]) ;
        PCHECK(retval);
      }

  }
```

(very) Basic usage of PAPI

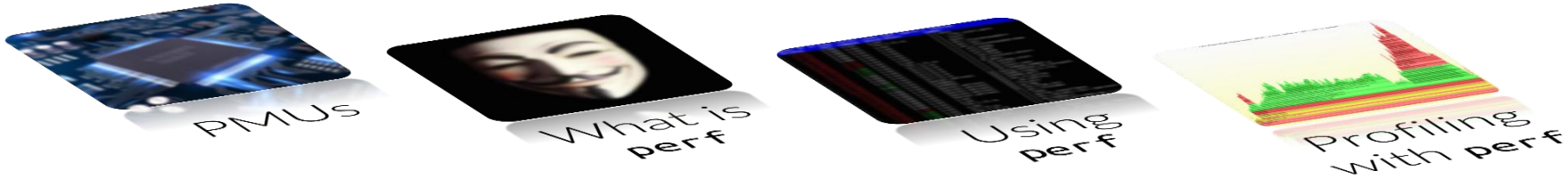
```
retval = PAPI_start_counters(events,NEVENTS); PCHECK(retval);
/* run the experiment */
for (i=0; i<NRUNS; i++)
  {
    for (j=0; j<size; j++) array[j] = 2.3*array[j]+1.2;
  }

retval = PAPI_stop_counters(values,NEVENTS); PCHECK(retval);

printf("size: %d cycles: %lld cycles_per_loc: %9.5f L1miss: %lld <..>
       size,
       values[0], values[0]/(1.*NRUNS*size),
       values[1], (double)values[1]/(NRUNS*size),
       values[2], (double)values[2]/(NRUNS*size));
```

Start, stop and access

Outline



Addendum II

Using `gperftools`

Use `gperftools` to obtain a basic profile

OPTION I

– Include gperftools/profiler.h:

```
#include <gperftools/profiler.h>
```

– Encompass the code segments to be profiled within calls:

```
ProfilerStart ( “name_of_profile_file” );
…
ProfilerStop ( );
```

– Then variable CPUPROFILEFREQUENCY=x modifies the sampling frequency (x is in Hz)

OPTION II

– link exec. against libprofiler.so

```
cc source.c –o exec -lprofiler
```

– or pre-load the profiler library

```
LD_PRELOAD=/path/to/libprofiler.so ./exec
```

– set variables CPUPROFILE to start the profiling

```
LD_PRELOAD=/path/to/libprofiler.so \
CPUPROFILE=./exec.prof CPUFREQUENCY=1000 \
./exec parameters
```

Use `gperftools` to obtain a basic profile

READ THE **GPERFTOOLS** DATA

Use pprof, interactive mode:

```
pprof ./exec ./exec.prof
```

… let's have a live demonstration about:

top
- list
- disasm
- weblist
- gv / web

You can produce output on stdio:

```
pprof --text ./exec ./exec.prof
pprof --text --lines ./exec ./exec.prof
pprof --text --functions ./exec ./exec.prof
```

or in other image format

```
pprof <--gv|--web|--dot|--ps|--svg|--gif>
```

or output to be pipelined elsewhere

```
pprof <--raw|--collapsed|--callgrind>
```

or the whole call stack in detail

```
pprof --text --stack
```