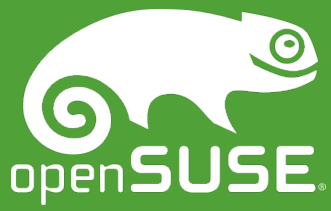
Introduction to performance analysis in openSUSE®

Using Perf



Tony Jones – Senior Software Engineer

SUSE Labs Portland, Oregon USA tonyj@suse.com

Give yourself a break

- Performance analysis is not easy
- It’s rarely black and white, more shades of grey.
- Lots of subjectivity

Methodologies and practice are useful

- Methodologies are useful, there are lots of them.
- → be methodical
- If you have to dig in, know what options exist.
- Write code to test hypothesis/understand tools.

There are lots of tools, perf is one

- And it’s not the first one you want to use.
  - dmesg/syslog
  - top
  - iostat/vmstat
  - Iotop
  - pidstat
  - strace

Performance Counters

- Hardware resource to aid performance analysis.
- Available on x86 since Pentium 3.
- Availability via CPUID and MSR
- Basic PMU functionality “standardized” with arch_perfmon_v1 thru v4
- Beyond this, additional PMUs micro-architecture specific

Perfmon

- Perfmon 2.0 designed by HP for ia64.
- Still in kernel tree for ia64.
- Extended for other architectures as Perfmon 2.X.
- Submission to LKML in 2008 led to counter submission of Performance Counters For Linux
- libpfm v4 still relevant today

Perf

- Introduced in 2009 in as Performance Counters for Linux, kernel version 2.6.31
- Now known as ‘perf events’
- A swiss-army knife but still mostly focused on cpu usage and integration with tracing.

Where to begin

- Install perf :)
- perf cmd
  - top
  - list
  - record
  - report
  - annotate
  - trace

Available events

- perf list

```
# perf list
cache-misses                                       [Hardware event]
cpu-cycles OR cycles                               [Hardware event]
instructions                                       [Hardware event]
...
context-switches OR cs                             [Software event]
cpu-migrations OR migrations                       [Software event]
...
L1-dcache-loads                                    [Hardware cache event]
...
dTLB-load-misses                                   [Hardware cache event]
...
rNNN                                               [Raw hardware event descriptor]
...
ext4:ext4_alloc_da_blocks                          [Tracepoint event]
...
module:module_free                                 [Tracepoint event]
...
net:netif_rx                                       [Tracepoint event]
...
sched:sched_switch                                 [Tracepoint event]
...
signal:signal_deliver                              [Tracepoint event]
..
syscalls:sys_enter_chroot                          [Tracepoint event]
..
syscalls:sys_exit_kexec_load                       [Tracepoint event]
```

Event monikers

```
intel# grep "model name" /proc/cpuinfo | uniq
model name  : Intel(R) Xeon(R) CPU E5-2420 v2 @ 2.20GHz

intel# ls /sys/devices/cpu/events/
branch-instructions  cache-misses      instructions  ref-cycles
branch-misses        cache-references  mem-loads     stalled-cycles-frontend
bus-cycles           cpu-cycles        mem-stores

intel# cat /sys/devices/cpu/events/cpu-cycles
event=0x3c

# /usr/bin/showevtinfo > /tmp/events

IDX      : 37748736
PMU name : ix86arch (Intel X86 architectural PMU)
Name     : UNHALTED_CORE_CYCLES
Equiv    : None
Flags    : None
Desc     : count core clock cycles whenever the clock signal on the specific core is running (not
halted)
Code     : 0x3c
Modif-00 : 0x00 : PMU : [k] : monitor at priv level 0 (boolean)
Modif-01 : 0x01 : PMU : [u] : monitor at priv level 1, 2, 3 (boolean)
Modif-02 : 0x02 : PMU : [e] : edge level (may require counter-mask >= 1) (boolean)
Modif-03 : 0x03 : PMU : [i] : invert (boolean)
Modif-04 : 0x04 : PMU : [c] : counter-mask in range [0-255] (integer)
Modif-05 : 0x05 : PMU : [t] : measure any thread (boolean)
```

Event monikers (cont)

```
amd# grep "model name" /proc/cpuinfo | uniq
model name  : AMD Opteron(tm) Processor 6128

amd# ls /sys/devices/cpu/events/
branch-instructions  cache-misses      cpu-cycles
branch-misses        cache-references  instructions

amd# cat /sys/devices/cpu/events/cpu-cycles
event=0x76

# /usr/bin/showevtinfo > /tmp/events

[amd]
IDX      : 134217766
PMU name : amd64_fam10h_istanbul (AMD64 Fam10h Istanbul)
Name     : CPU_CLK_UNHALTED
Equiv    : None
Flags    : None
Desc     : CPU Clocks not Halted
Code     : 0x76
Modif-00 : 0x00 : PMU : [k] : monitor at priv level 0 (boolean)
Modif-01 : 0x01 : PMU : [u] : monitor at priv level 1, 2, 3 (boolean)
Modif-02 : 0x02 : PMU : [e] : edge level (boolean)
Modif-03 : 0x03 : PMU : [i] : invert (boolean)
Modif-04 : 0x04 : PMU : [c] : counter-mask in range [0-255] (integer)
Modif-05 : 0x05 : PMU : [h] : monitor in hypervisor (boolean)
Modif-06 : 0x06 : PMU : [g] : measure in guest (boolean)
```

Sampling vs counting

- Counters operate in two distinct ways
  - Counted.
  - Sampled.

- Sampling rate can be specified via either
  - Frequency (-F)
  - Count (-c)

Perf top

- Perf top. Sampling view similar to standard UNIX utility
- Provides view into where cpu is spending time. Not everything is user cpu bound (0.1% user, 4.1% sys)

```
Samples: 32K of event 'cycles:ppp', Event count (approx.): 8956122825
Overhead  Shared Object       Symbol
  44.93%  [kernel]            [k] _raw_spin_lock
  36.76%  [kernel]            [k] sync_inodes_sb
   1.78%  [kernel]            [k] _raw_spin_unlock
   0.78%  [kernel]            [k] __filemap_fdatawait_range
   0.58%  [kernel]            [k] find_get_pages_tag
   0.56%  [kernel]            [k] _atomic_dec_and_lock
   0.50%  [kernel]            [k] __iget
   0.45%  [kernel]            [k] nmi
   0.41%  [kernel]            [k] iput
   0.36%  [kernel]            [k] unmap_page_range
   0.32%  [kernel]            [k] __wake_up_bit
   0.25%  [kernel]            [k] filemap_map_pages
   0.23%  [kernel]            [k] clear_page_c_e
   0.22%  [kernel]            [k] copy_page
...
...
```

Perf top (cont)

- Sometimes it is (top reports 100% user, 0% sys)

```
Samples: 867K of event 'cycles:ppp', Event count (approx.): 340340242278
Overhead  Shared Object       Symbol
  51.02%  libcrypto.so.1.0.0  [.] DES_set_key_unchecked
  26.95%  libcrypto.so.1.0.0  [.] DES_encrypt1
   1.07%  libcrypto.so.1.0.0  [.] DES_set_odd_parity
   0.53%  libcrypto.so.1.0.0  [.] EVP_DigestInit_ex
   0.44%  libc-2.23.so        [.] _int_free
   0.39%  libcrypto.so.1.0.0  [.] EVP_Digest
   0.38%  libc-2.23.so        [.] _int_malloc
   0.30%  libcrypto.so.1.0.0  [.] EVP_MD_CTX_cleanup
   0.29%  libc-2.23.so        [.] malloc
...
```

Perf top (cont)

- Possible to annotate hot code
- Enable callgraphs (-g) to show paths to hot code
- Two types of callgraphs for userspace. Frame pointer and dwarf

```
# zcat /proc/config.gz | egrep -e "CONFIG_FRAME_POINTER|UNWIND"
CONFIG_UNWIND_INFO=y
CONFIG_STACK_UNWIND=y
# CONFIG_FRAME_POINTER is not set
```

Perf record

- Samples counters for later analysis.
- Lots of command line options:
  - perf record *command*
  - perf record -a *command*
  - perf record -a
- Default scope is kernel+usermode
  - perf record -e cpu-cycles:u *command*
  - perf record -a -e cpu-cycles:k

Perf record

```
# perf record -c 1000 -e instructions:u ./linpack 200

# perf report -D | grep -c PERF_RECORD_SAMPLE
3048011

# perf report -n --stdio
# Total Lost Samples: 0
#
# Samples: 3M of event 'instructions:u'
# Event count (approx.): 3048011000
#
# Overhead       Samples  Command  Shared Object      Symbol
# ........  ............  .......  .................  ..................................
    48.04%       1464144  linpack  linpack            [.] daxpy_r
    40.31%       1228752  linpack  linpack            [.] daxpy_ur
     7.72%        235359  linpack  linpack            [.] matgen
     2.05%         62548  linpack  linpack            [.] dgefa
     0.83%         25291  linpack  linpack            [.] idamax
     0.52%         15798  linpack  linpack            [.] dscal_r
     0.41%         12496  linpack  linpack            [.] dscal_ur
     0.11%          3337  linpack  linpack            [.] dgesl
     0.00%            56  linpack  libc-2.23.so       [.] _dl_addr
```

Perf record

```
# perf annotate --print-line --stdio daxpy_r
...
         :          /* code for both increments equal to 1 */
         :
         :          for (i = 0;i < n; i++)
    0.21 :        40200e:       movl   $0x0,-0x4(%rbp)
    0.00 :        402015:       jmp    40206e <daxpy_r+0x163>
         :              dy[i] = dy[i] + da*dx[i];
 linpack.c:599   10.24 :          402017:       mov    -0x4(%rbp),%eax
    0.28 :        40201a:       cltq
    0.01 :        40201c:       lea    0x0(,%rax,8),%rdx
    0.30 :        402024:       mov    -0x30(%rbp),%rax
   10.31 :        402028:       add    %rdx,%rax
    0.01 :        40202b:       mov    -0x4(%rbp),%edx
    0.04 :        40202e:       movslq %edx,%rdx
    0.33 :        402031:       lea    0x0(,%rdx,8),%rcx
   10.37 :        402039:       mov    -0x30(%rbp),%rdx
    0.00 :        40203d:       add    %rcx,%rdx
    0.01 :        402040:       movsd  (%rdx),%xmm1
 linpack.c:599    3.04 :          402044:       mov    -0x4(%rbp),%edx
 linpack.c:599    9.35 :          402047:       movslq %edx,%rdx
    0.00 :        40204a:       lea    0x0(,%rdx,8),%rcx
    0.00 :        402052:       mov    -0x28(%rbp),%rdx
 linpack.c:599    1.28 :          402056:       add    %rcx,%rdx
 linpack.c:599    9.58 :          402059:       movsd  (%rdx),%xmm0
 linpack.c:599    0.88 :          40205d:       mulsd  -0x20(%rbp),%xmm0
 linpack.c:599   10.86 :          402062:       addsd  %xmm1,%xmm0
   17.50 :        402066:       movsd  %xmm0,(%rax)
```

Perf record

```
# perf record -c 1000 -e instructions ./linpack 200
# perf report -n  --stdio | head -30

# Total Lost Samples: 0
#
# Samples: 1M of event 'instructions'
# Event count (approx.): 1868359000
#
# Overhead       Samples  Command  Shared Object      Symbol
    47.46%        886656  linpack  linpack            [.] daxpy_r
    40.03%        747911  linpack  linpack            [.] daxpy_ur
     8.32%        155453  linpack  linpack            [.] matgen
     1.60%         29808  linpack  linpack            [.] dgefa
     0.79%         14756  linpack  linpack            [.] idamax
     0.49%          9101  linpack  linpack            [.] dscal_r
     0.39%          7298  linpack  linpack            [.] dscal_ur
     0.26%          4825  linpack  [kernel.kallsyms]  [k] _raw_spin_lock_irq
     0.22%          4181  linpack  [kernel.kallsyms]  [k] __local_bh_enable
     0.10%          1833  linpack  [kernel.kallsyms]  [k] run_timer_softirq
     0.08%          1537  linpack  linpack            [.] dgesl
     0.03%           610  linpack  [kernel.kallsyms]  [k] __softirqentry_text_start
     0.03%           599  linpack  [kernel.kallsyms]  [k] idle_cpu
     0.01%           275  linpack  [kernel.kallsyms]  [k] load_balance
     0.01%           253  linpack  [kernel.kallsyms]  [k] _raw_spin_unlock_irq
     0.01%           226  linpack  [kernel.kallsyms]  [k] update_sd_lb_stats
     0.01%           159  linpack  [kernel.kallsyms]  [k] _raw_spin_unlock_irqrestore
     0.01%           159  linpack  [kernel.kallsyms]  [k] select_task_rq_fair
     0.01%           157  linpack  [kernel.kallsyms]  [k] enqueue_entity
```

What events should I monitor

- Instructions per cycle

```
# perf stat -e instructions:u -e cycles:u ./linpack 200

 Performance counter stats for './linpack 200':

    77,693,957,078      instructions:u            #    2.73  insn per cycle

    28,421,726,540      cycles:u

      25.760008514 seconds time elapsed
```

What events should I monitor

- Cache misses relative to references

```
#define MULT 8  // 1 == 8 * 1024 * 1024, ~8MB of 15MB L3 cache
int main()
{
int *p, i; const int num = MULT * 1024 * 1024, loops=50;

      if (!(p=malloc(num * sizeof(int))))
            return 1;

      srand((unsigned)time(NULL));

      for (i;i<num*loops;i++)
            p[rand() % num] += rand();

      free(p);
      return 0;
}

# perf stat -e cache-misses:u -e cache-references:u   ./badcache
 Performance counter stats for './badcache':

       227,020,317      cache-misses:u            #   54.474 % of all cache refs
       416,750,100      cache-references:u

      23.962244212 seconds time elapsed
```

What events should I monitor

- Cache misses relative to references

```
IDX      : 216006703
PMU name : ivb_ep (Intel Ivy Bridge EP)
Name     : MEM_LOAD_UOPS_RETIRED
Flags    : [precise]
Desc     : Memory loads uops retired
Code     : 0xd1
Umask-00 : 0x40 : PMU : [HIT_LFB] : [precise] : A load missed L1D but hit the Fill Buffer
Umask-01 : 0x01 : PMU : [L1_HIT] : [precise] : Load hit in nearest-level (L1D) cache
Umask-02 : 0x02 : PMU : [L2_HIT] : [precise] : Load hit in mid-level (L2) cache
Umask-03 : 0x10 : PMU : [L2_MISS] : [precise] : Load misses in mid-level (L2) cache
Umask-04 : 0x04 : PMU : [L3_HIT] : [precise] : Load hit in last-level (L3) cache with no snoop needed
Umask-05 : 0x20 : PMU : [L3_MISS] : [precise] : Load miss in last-level (L3) cache

# for i in L2_HIT L2_MISS L3_HIT L3_MISS; do echo -n "`/usr/bin/evt2raw MEM_LOAD_UOPS_RETIRED:$i` "; done
r5302d1 r5310d1 r5304d1 r5320d1

# perf stat -e r5302d1:u -e r5310d1:u -e r5304d1:u -e r5320d1:u ./badcache

 Performance counter stats for './badcache':

         2,875,282      r5302d1:u                                     (50.00%)
       412,616,740      r5310d1:u                                     (50.01%)
       187,720,675      r5304d1:u                                     (50.00%)
       224,533,511      r5320d1:u                                     (49.99%)

      36.058470947 seconds time elapsed
```

What events should I monitor

- Branch misses relative to branch instructions

```
enum{size = 8}; int t[size] = {0,0,0,0,0,0,0,0};

void func(int _v)
{
#define DO(x) if (_v == x) t[x]++
#define EDO(x) else DO(x)

      DO(0); EDO(1); EDO(2); EDO(3); EDO(4); EDO(5); EDO(6); EDO(7);
}

int main()
{
int i;
volatile int v;
const int num = 20 * 1024 * 1024;

      srand((unsigned)time(NULL));

      for (i=0;i<num;i++){
            v=rand() % size;
            func(v);
      }

      //for (i=0;i<size;i++)
      //    printf("t[%d]=%d\n", i, t[i]);
}
```

What events should I monitor

- Counted

```
# perf stat  -e branches:u -e branch-misses:u branch_8x

 Performance counter stats for 'branch_8x':

       490,265,094      branches:u
        19,435,491      branch-misses:u           #    3.96% of all branches

       1.361357178 seconds time elapsed
```

What events should I monitor

- Sampled

```
# perf record -e branches:u -e branch-misses:u branch_8x

# perf report -n --stdio --dsos branch_8x
# dso: branch_8x
#
# Samples: 2K of event 'branches:u'
# Event count (approx.): 490409129
# Overhead       Samples  Command    Symbol
    42.50%          1196  branch_8x  [.] func
    21.67%           609  branch_8x  [.] main

# Samples: 2K of event 'branch-misses:u'
# Event count (approx.): 19453325
# Overhead       Samples  Command    Symbol
    73.30%          2058  branch_8x  [.] func
    23.79%           669  branch_8x  [.] main
```

Sampling skew/skid

- When a performance counter overflows, IP passed.
- On heavily pipelined architectures reported IP may not be correct
- PEBS, precise event based sampling
- Specified via the precision qualifier (0 to 3)
  - event:p [1, skid shall be constant]
  - event:pp [2, request 0 skid]
  - event:ppp [3, require 0 skid]

Tracing and tracepoints

- perf list tracepoint

```
# perf list tracepoint
List of pre-defined events (to be used in -e):
  block:block_bio_backmerge                          [Tracepoint event]
...
  sched:sched_switch                                 [Tracepoint event]
...
  syscalls:sys_enter_accept                          [Tracepoint event]
...
  syscalls:sys_exit_accept                           [Tracepoint event]

# cat /sys/kernel/debug/tracing/events/sched/sched_switch/format
name: sched_switch
ID: 273
format:
      field:unsigned short common_type;   offset:0;   size:2;     signed:0;
      field:unsigned char common_flags;   offset:2;   size:1;     signed:0;
      ...
print fmt: "prev_comm=%s prev_pid=%d prev_prio=%d prev_state=%s%s ==> next_comm=%s
next_pid=%d next_prio=%d", REC->prev_comm, REC->prev_pid, REC->prev_prio, REC->prev_state
& (2048-1) ? __print_flags(REC->prev_state & (2048-1), "|", { 1, "S"} , { 2, "D" }, { 4,
"T" }, { 8, "t" }, { 16, "Z" }, { 32, "X" }, { 64, "x" }, { 128, "K" }, { 256, "W" },
{ 512, "P" }, { 1024, "N" }) : "R", REC->prev_state & 2048 ? "+" : "", REC->next_comm,
REC->next_pid, REC->next_prio
```

Tracing and tracepoints

- perf stat -a -e ‘syscalls:sys_enter_*’ sleep 30
- perf stat -e ‘sched:sched_switch’ ./benchmark
- perf record -a -g -e ‘syscalls:sys_enter_write’ --filter ‘count > 1024’

```
# tail -1 /sys/kernel/debug/tracing/events/syscalls/sys_enter_write/format
print fmt: "fd: 0x%08lx, buf: 0x%08lx, count: 0x%08lx", ((unsigned long)(REC->fd)),
((unsigned long)(REC->buf)), ((unsigned long)(REC->count))
```

Perf trace

- Track costly syscalls

```
# perf trace --duration 1.0 dd if=/dev/zero of=/tmp/out bs=1k count=10
10+0 records in
10+0 records out
10240 btes (10 kB, 10 KiB) copied, 0.000448134 s, 22.9 MB/s

# perf trace --duration 1.0 dd if=/dev/zero of=/tmp/out bs=1k count=10 conv=fdatasync
     8.652 ( 6.035 ms): dd/9820 fdatasync(fd: 1</tmp/out>                                                ) = 0
10+0 records in
10+0 records out
10240 bytes (10 kB, 10 KiB) copied, 0.00663256 s, 1.5 MB/s

# perf trace --duration 1.0 dd if=/dev/zero of=/tmp/out bs=1k count=10 oflag=sync
     7.795 ( 6.127 ms): dd/9847 write(fd: 1</tmp/out>, buf: 0x559fbf625000, count: 1024              ) = 1024
     9.278 ( 1.463 ms): dd/9847 write(fd: 1</tmp/out>, buf: 0x559fbf625000, count: 1024              ) = 1024
    10.746 ( 1.448 ms): dd/9847 write(fd: 1</tmp/out>, buf: 0x559fbf625000, count: 1024              ) = 1024
    12.195 ( 1.418 ms): dd/9847 write(fd: 1</tmp/out>, buf: 0x559fbf625000, count: 1024              ) = 1024
    13.704 ( 1.486 ms): dd/9847 write(fd: 1</tmp/out>, buf: 0x559fbf625000, count: 1024              ) = 1024
    15.312 ( 1.564 ms): dd/9847 write(fd: 1</tmp/out>, buf: 0x559fbf625000, count: 1024              ) = 1024
    16.754 ( 1.419 ms): dd/9847 write(fd: 1</tmp/out>, buf: 0x559fbf625000, count: 1024              ) = 1024
    18.214 ( 1.437 ms): dd/9847 write(fd: 1</tmp/out>, buf: 0x559fbf625000, count: 1024              ) = 1024
    19.741 ( 1.503 ms): dd/9847 write(fd: 1</tmp/out>, buf: 0x559fbf625000, count: 1024              ) = 1024
    21.200 ( 1.431 ms): dd/9847 write(fd: 1</tmp/out>, buf: 0x559fbf625000, count: 1024              ) = 1024
```

Perf trace

- Summary of syscalls

```
# perf trace -s dd if=/dev/zero of=/tmp/out bs=1k count=10
10+0 records in
10+0 records out
10240 bytes (10 kB, 10 KiB) copied, 0.000364407 s, 28.1 MB/s

 Summary of events:

 dd (9990), 305 events, 97.8%, 0.000 msec

   syscall            calls    total       min       avg       max      stddev
                               (msec)    (msec)    (msec)    (msec)        (%)
   --------------- -------- --------- --------- --------- ---------     ------
   read                13      0.032     0.002     0.002     0.004      9.14%
   write               13      0.102     0.004     0.008     0.021     17.20%
   open                50      0.257     0.003     0.005     0.057     21.01%
   close               22      0.037     0.001     0.002     0.002      2.77%
   fstat               17      0.037     0.002     0.002     0.005      9.72%
   lseek                1      0.002     0.002     0.002     0.002      0.00%
   mmap                21      0.118     0.003     0.006     0.009      5.66%
   mprotect             4      0.030     0.004     0.008     0.012     23.08%
   munmap               1      0.010     0.010     0.010     0.010      0.00%
   brk                  3      0.009     0.002     0.003     0.004     23.94%
   rt_sigaction         3      0.005     0.001     0.002     0.002     14.85%
   access               1      0.006     0.006     0.006     0.006      0.00%
   Dup2                 2      0.005     0.002     0.002     0.003      8.43%
   arch_prctl           1      0.002     0.002     0.002     0.002      0.00%
```

Perf probe

- Dynamically created tracepoints

```
# perf probe _copy_from_user
Added new event:
  probe:_copy_from_user (on _copy_from_user)

You can now use it in all perf tools, such as:

      perf record -e probe:_copy_from_user -aR sleep 1
```

- Count or sample

```
# perf stat -a -e probe:_copy_from_user sleep 1

 Performance counter stats for 'system wide':

             1,209      probe:_copy_from_user

       1.001884191 seconds time elapsed
```

Scripting

- perf script
- perf script -l
- perf script -g [python|perl]
- perf script record <script> [perf record options]
- perf script report <script> [script options]

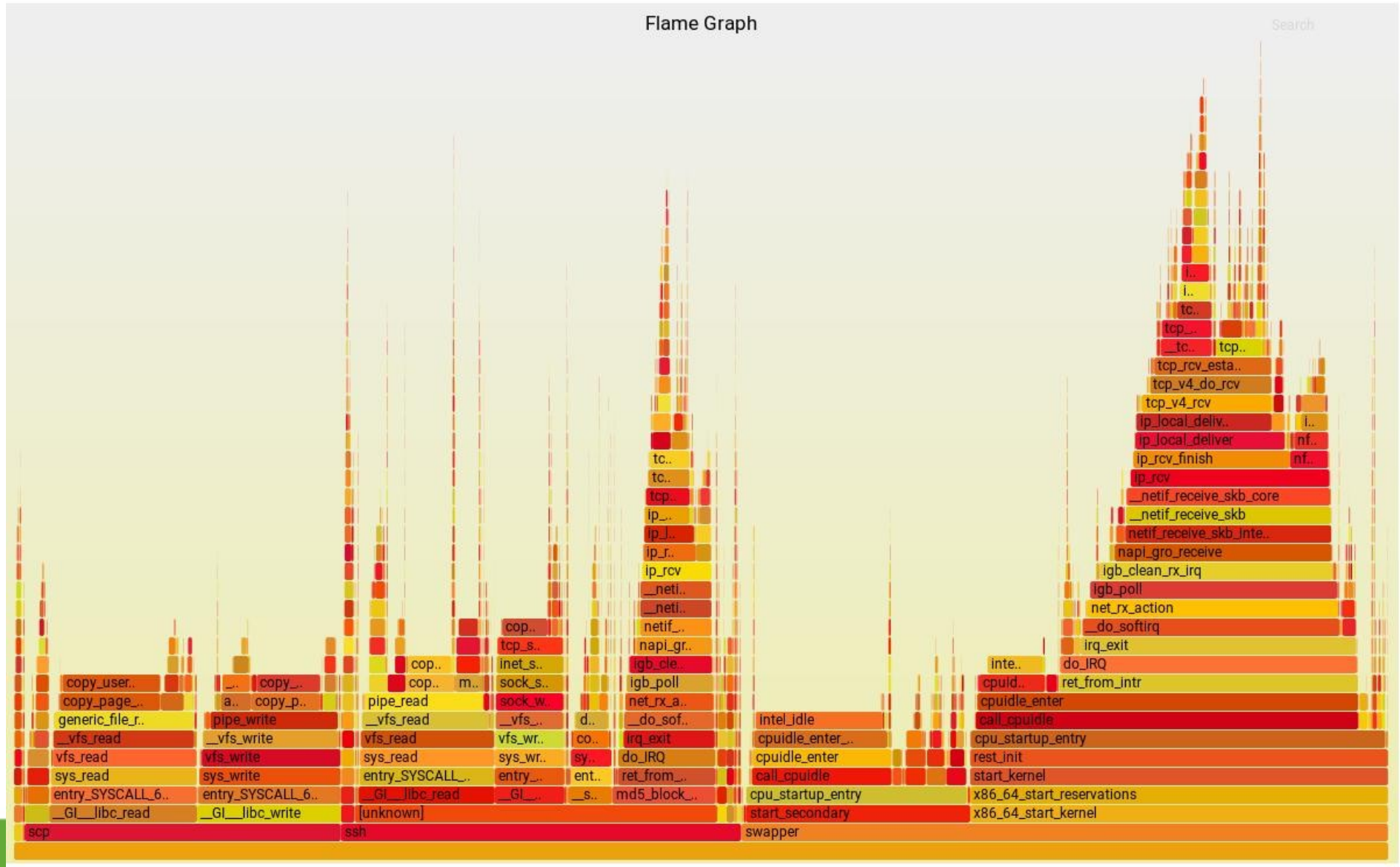
Advanced topics

Flame Graphs

http://www.brendangregg.com/FlameGraphs/cpuflamegraphs.html

- perf record -a -g -e cycles:k scp /tmp/file.10gb host:
- perf script | stackcollapse-perf.pl | flamegraph.pl > data.svg
- firefox data.svg

Flame Graphs



PAPI / self-monitoring

- Performance Application Programming Interface
- http://icl.cs.utk.edu/papi/
  - Has it's own event monikers termed "event presets"s but can work with perf raw event codes.
- Alternative: see implemention of tools/perf/tests/rdpmc.c
  - http://web.eece.maine.edu/~vweaver/projects/perf_events/overhead/2015_ispass_overhead.pdf
  - Mainline commits fe4a3308 and 08aa0d1f

Off-cpu analysis

- Monitoring time spent not running.
- Many reasons
  - disc io
  - synchronization (locks, mutexes, signals)
  - virtual memory
  - context switching
- http://www.brendangregg.com/offcpuanalysis.html

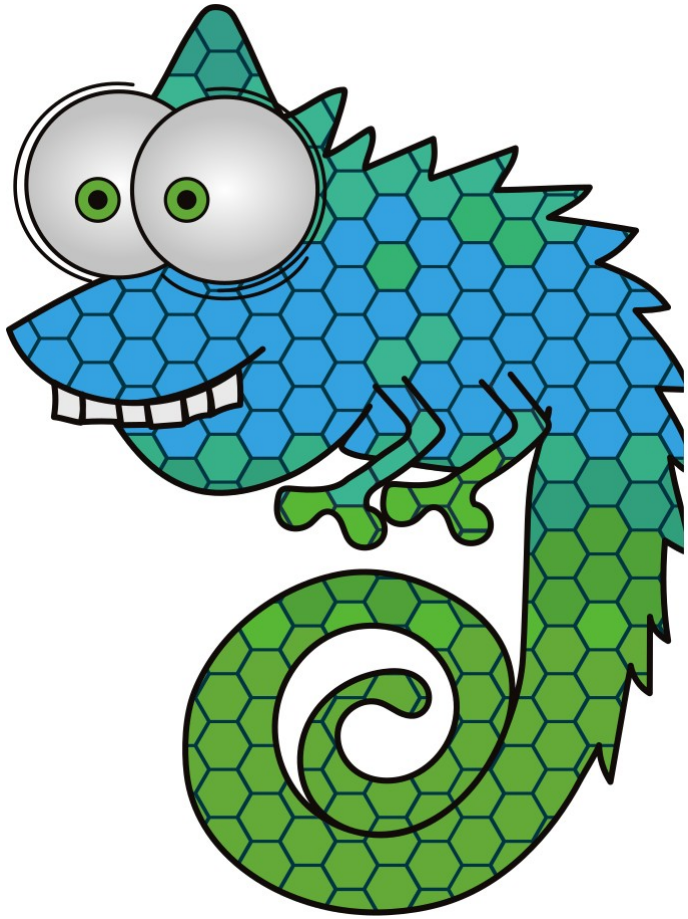
Virtualization

- Monitoring guest requires virtualization of pmu hardware.
- Xen DomU reports software/tracepoint only
- QEMU: use ‘-cpu *,pmu=on’ or ‘-cpu host’ (kvm)
- Use perf kvm to monitor guest

Questions?

Thanks for listening. Further questions welcomed via email. Bug reports are great too.

Thank you.



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