Benchmarking and instrumentation

More caches and pipelines

- recall that memory is virtualized
- a virtual address → hardware address translation is necessary for every memory access
- the translation uses a page table
- the page table is stored in memory
- hence at least two effective memory accesses per memory fetch instruction?

Solution: part of the page table is **cached** in the CPU

the “Translation Lookaside Buffer” (TLB)

Caches and pipelines are used at various levels to hide access latency

	typical latency		
instruction	~0.25 ns	`0.25`	`ns`
RAM	~100 ns	`100`	`ns`
solid state drive (SSD)	~0.2 ms	`200,000`	`ns`
hard disk drive (HDD)	~2 ms	`2,000,000`	`ns`
wired ethernet (round-trip)	~1 ms	`1,000,000`	`ns`
wifi latency (round-trip)	~10 ms	`10,000,000`	`ns`
same-city internet (round-trip)	~5 ms	`5,000,000`	`ns`
same-continent internet (round-trip)	~25 ms	`25,000,000`	`ns`
transatlantic internet (round-trip)	~100 ms	`100,000,000`	`ns`

Examples of caches

- SSDs have internal RAM caches (typically 0-4 GB)
- the operating system caches files in memory
- large content providers (Google, Amazon, Netflix, Cloudflare) have caches all over the world

```
ping math.uwaterloo.ca
```

```
PING math.uwaterloo.ca (129.97.206.16) 56(84) bytes of data.
64 bytes from ingress-p01.math.uwaterloo.ca (129.97.206.16): icmp_seq=1 ttl=43 time=110 ms
64 bytes from ingress-p01.math.uwaterloo.ca (129.97.206.16): icmp_seq=2 ttl=43 time=110 ms
64 bytes from ingress-p01.math.uwaterloo.ca (129.97.206.16): icmp_seq=3 ttl=43 time=111 ms
64 bytes from ingress-p01.math.uwaterloo.ca (129.97.206.16): icmp_seq=4 ttl=43 time=111 ms
```

```
ping google.com.au
```

```
PING google.com.au (142.251.209.3) 56(84) bytes of data.
64 bytes from mil04s50-in-f3.1e100.net (142.251.209.3): icmp_seq=1 ttl=115 time=12.2 ms
64 bytes from mil04s50-in-f3.1e100.net (142.251.209.3): icmp_seq=2 ttl=115 time=14.6 ms
64 bytes from mil04s50-in-f3.1e100.net (142.251.209.3): icmp_seq=3 ttl=115 time=12.9 ms
64 bytes from mil04s50-in-f3.1e100.net (142.251.209.3): icmp_seq=4 ttl=115 time=11.8 ms
```

Examples of pipelines

- Storage devices:
  - SSDs typically access data in “pages” of **4096 bytes**
  - **0.2ms** SSD latency would imply a max speed of 20 MB / s
  - instead SSDs routinely read and write 500 MB / s

- Networks:
  - Network packets are typically **1500 bytes**
  - **10ms** WiFi latency would imply 150 KB / s
  - instead most WiFi networks do at least 10,000 KB / s

- Browsers:
  - Google Chrome maintains up to **6** connections per domain

Benchmarking

```
time ./application
```

```
real    0m2.501s
user    0m2.498s
sys     0m0.001s
```

- `real`: elapsed “real” (wall-clock) time
- `user`: time spent in user mode (running `./application` code)
- `sys`: time spent in system mode (running OS kernel code)
- $\texttt{user} + \texttt{sys} \lesssim \texttt{real}$ (there may be other applications running)

```
time head -n 1000000 /dev/random > /dev/null
```

```
real	0m0.444s
user	0m0.066s
sys	0m0.377s
```

Variance

```
time head -n 1000000 /dev/random > /dev/null
```

```
real	0m0.442s
user	0m0.070s
sys	0m0.371s
```

```
time head -n 1000000 /dev/random > /dev/null
```

```
real	0m0.448s
user	0m0.066s
sys	0m0.381s
```

```
time head -n 1000000 /dev/random > /dev/null
```

```
real	0m0.445s
user	0m0.056s
sys	0m0.388s
```

Reasons for variance

- throttling for temperature and power limits

  (CPU adapts speed to avoid overheating or exceeding power supply capabilities)

- interactions with devices

  (OS has in-memory caches for files, storage devices have internal memory caches)

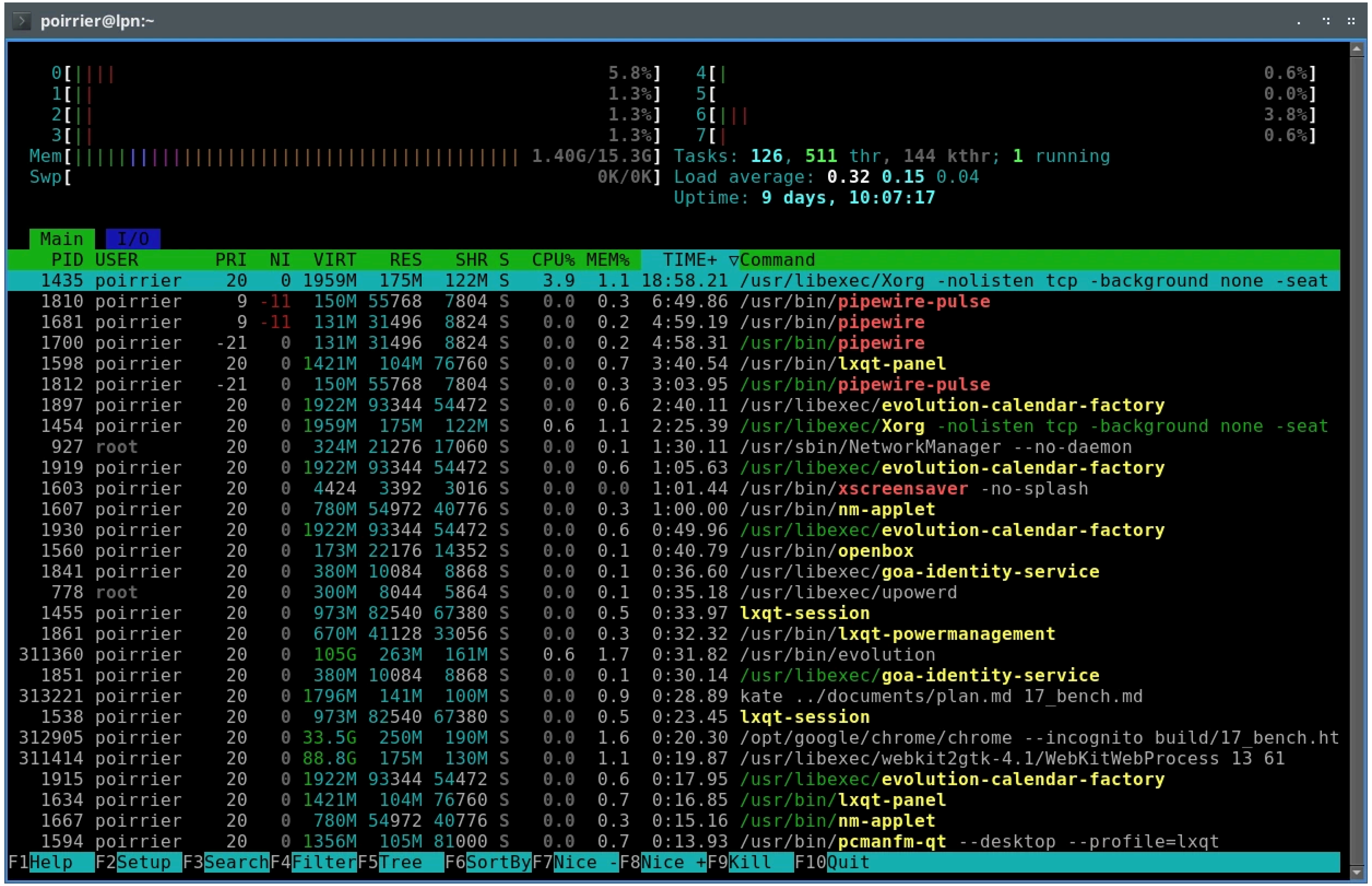
- other processes

  (must share resources)

`top`

`htop`

`ps aux`



```
    0[||||                                            5.8%]   4[|                                           0.6%]
    1[||                                              1.3%]   5[                                            0.0%]
    2[||                                              1.3%]   6[|||                                         3.8%]
    3[||                                              1.3%]   7[|                                           0.6%]
  Mem[|||||||||||||||||||||||||||||||||||||||||  1.40G/15.3G] Tasks: 126, 511 thr, 144 kthr; 1 running
  Swp[                                                0K/0K] Load average: 0.32 0.15 0.04
                                                             Uptime: 9 days, 10:07:17

  Main  I/O
    PID USER      PRI  NI  VIRT   RES   SHR S  CPU% MEM%   TIME+ ▽Command
   1435 poirrier   20   0 1959M  175M  122M S   3.9  1.1 18:58.21 /usr/libexec/Xorg -nolisten tcp -background none -seat
   1810 poirrier    9 -11  150M 55768  7804 S   0.0  0.3  6:49.86 /usr/bin/pipewire-pulse
   1681 poirrier    9 -11  131M 31496  8824 S   0.0  0.2  4:59.19 /usr/bin/pipewire
   1700 poirrier  -21   0  131M 31496  8824 S   0.0  0.2  4:58.31 /usr/bin/pipewire
   1598 poirrier   20   0 1421M  104M 76760 S   0.0  0.7  3:40.54 /usr/bin/lxqt-panel
   1812 poirrier  -21   0  150M 55768  7804 S   0.0  0.3  3:03.95 /usr/bin/pipewire-pulse
   1897 poirrier   20   0 1922M 93344 54472 S   0.0  0.6  2:40.11 /usr/libexec/evolution-calendar-factory
   1454 poirrier   20   0 1959M  175M  122M S   0.6  1.1  2:25.39 /usr/libexec/Xorg -nolisten tcp -background none -seat
    927 root       20   0  324M 21276 17060 S   0.0  0.1  1:30.11 /usr/sbin/NetworkManager --no-daemon
   1919 poirrier   20   0 1922M 93344 54472 S   0.0  0.6  1:05.63 /usr/libexec/evolution-calendar-factory
   1603 poirrier   20   0  4424  3392  3016 S   0.0  0.0  1:01.44 /usr/bin/xscreensaver -no-splash
   1607 poirrier   20   0  780M 54972 40776 S   0.0  0.3  1:00.00 /usr/bin/nm-applet
   1930 poirrier   20   0 1922M 93344 54472 S   0.0  0.6  0:49.96 /usr/libexec/evolution-calendar-factory
   1560 poirrier   20   0  173M 22176 14352 S   0.0  0.1  0:40.79 /usr/bin/openbox
   1841 poirrier   20   0  380M 10084  8868 S   0.0  0.1  0:36.60 /usr/libexec/goa-identity-service
    778 root       20   0  300M  8044  5864 S   0.0  0.1  0:35.18 /usr/libexec/upowerd
   1455 poirrier   20   0  973M 82540 67380 S   0.0  0.5  0:33.97 lxqt-session
   1861 poirrier   20   0  670M 41128 33056 S   0.0  0.3  0:32.32 /usr/bin/lxqt-powermanagement
 311360 poirrier   20   0  105G  263M  161M S   0.6  1.7  0:31.82 /usr/bin/evolution
   1851 poirrier   20   0  380M 10084  8868 S   0.0  0.1  0:30.14 /usr/libexec/goa-identity-service
 313221 poirrier   20   0 1796M  141M  100M S   0.0  0.9  0:28.89 kate ../documents/plan.md 17_bench.md
   1538 poirrier   20   0  973M 82540 67380 S   0.0  0.5  0:23.45 lxqt-session
 312905 poirrier   20   0 33.5G  250M  190M S   0.0  1.6  0:20.30 /opt/google/chrome/chrome --incognito build/17_bench.ht
 311414 poirrier   20   0 88.8G  175M  130M S   0.0  1.1  0:19.87 /usr/libexec/webkit2gtk-4.1/WebKitWebProcess 13 61
   1915 poirrier   20   0 1922M 93344 54472 S   0.0  0.6  0:17.95 /usr/libexec/evolution-calendar-factory
   1634 poirrier   20   0 1421M  104M 76760 S   0.0  0.7  0:16.85 /usr/bin/lxqt-panel
   1667 poirrier   20   0  780M 54972 40776 S   0.0  0.3  0:15.16 /usr/bin/nm-applet
   1594 poirrier   20   0 1356M  105M 81000 S   0.0  0.7  0:13.93 /usr/bin/pcmanfm-qt --desktop --profile=lxqt
F1Help  F2Setup F3SearchF4FilterF5Tree  F6SortByF7Nice -F8Nice +F9Kill  F10Quit
```

(271 processes)

Effect of file caches

```
time md5sum 2GB_file
```

```
860a0023a913fd3fa4b6ad8bfbdd2c62  2GB_file

real    0m5.904s
user    0m4.062s
sys     0m0.560s
```

```
time md5sum 2GB_file
```

```
860a0023a913fd3fa4b6ad8bfbdd2c62  2GB_file

real    0m4.029s
user    0m3.674s
sys     0m0.331s
```

Inaccuracies

- executable startup is slow
- initialization adds overhead
- input and output are slow

Executable startup is slow

```
int main() { return 0; }
```

```
clang -O3 -o main main.c
time ./main
```

```
real	0m0.003s
user	0m0.000s
sys	0m0.002s
```

```
time python -c 'exit(0)'
```

```
real	0m0.030s
user	0m0.023s
sys	0m0.008s
```

⟶ we cannot accurately benchmark application that only take a few milliseconds.

Initialization adds overhead

```
time glpsol LP_576x18380.mps
```

```
real	0m0.256s
user	0m0.246s
sys	0m0.010s
```

```
time glpsol --check LP_576x18380.mps
```

```
real	0m0.168s
user	0m0.161s
sys	0m0.008s
```

What are we really measuring?

The speed of the MPS file parser, not the simplex algorithm.

Input and output are slow

```python
def riemann_zeta(s):
    r = 0.0

    for i in range(1, 1000000):
        r += 1 / (i ** s)

    return r

# ζ(2) = (pi ** 2) / 6
print('pi ≈ ', (riemann_zeta(2) * 6) ** 0.5)
```

```
time python zeta.py
```

```
pi ≈  3.141591698659554

real    0m0.124s
user    0m0.118s
sys     0m0.006s
```

```python
def riemann_zeta(s):
    r = 0.0

    for i in range(1, 1000000):
        r = r + 1 / (i ** s)
        print('r = ', r)

    return r

# ζ(2) = (pi ** 2) / 6
print('pi ≈ ', (riemann_zeta(2) * 6) ** 0.5)
```

```
time python zeta.py
```

```
r =  1.0
r =  1.25
r =  1.3611111111111112
r =  1.4236111111111112
r =  1.4636111111111112
r =  1.4913888888888889
r =  1.511797052154195

       [...]

r =  1.6449330668467699
r =  1.64493306684777
pi ≈  3.141591698659554

real    0m3.768s
user    0m2.516s
sys     0m0.999s
```

Aggregate measures

- if we benchmark our code on different inputs, we may want to use
    - total time / average time
    - geometric mean
    - or other aggregate measures
    - or some visualization (bar graphs, performance profiles, etc.)

- but beware: all aggregate measures are biased

	Input 1		**Input 2**		**Input 3**		**Average**
Version A	2530s		2300s		12s		1614s
Version B	2535s	1.002x	2304s	1.002x	6s	0.5x	1615s

Static instrumentation

- we may want to benchmark specific parts of our code
    - to circumvent executable startup, initialization, and input/output
    - to benchmark parts of the code that run quickly
    - to find bottlenecks

- for that, we need to add timing instrumentation to our code

About bottlenecks

> “Premature optimization is the root of all evil”

– Donald Knuth
“Structured Programming With GoTo Statements”
1974

`function_A()`	12% time	500 lines of code
`function_B()`	60% time	20 lines of code
`function_C()`	18% time	80 lines of code
all the rest	10% time	2000 lines of code

time.time()

```
initialize()
function_A()
function_B()
function_C()
cleanup()
```

```python
import time

t0 = time.time()
initialize()

t1 = time.time()
function_A()

t2 = time.time()
function_B()

t3 = time.time()
function_C()

t4 = time.time()
cleanup()

t5 = time.time()

print(f'total time: {t5 - t0:16.6f}')

print(f'function_A: {t2 - t1:16.6f}')
print(f'function_B: {t3 - t2:16.6f}')
print(f'function_C: {t4 - t3:16.6f}')

print(f'      rest: {(t5 - t0) - (t4 - t1):16.6f}')
```

clock_gettime()

```c
int main()
{
    initialize();
    function_A();
    function_B();
    function_C();
    cleanup();
    return 0;
}
```

```c
int main()
{
    struct timespec t0, t1, t2, t3, t4, t5;

    clock_gettime(CLOCK_MONOTONIC, &t0);
    initialize();

    clock_gettime(CLOCK_MONOTONIC, &t1);
    function_A();

    clock_gettime(CLOCK_MONOTONIC, &t2);
    function_B();

    clock_gettime(CLOCK_MONOTONIC, &t3);
    function_C();

    clock_gettime(CLOCK_MONOTONIC, &t4);
    cleanup();

    clock_gettime(CLOCK_MONOTONIC, &t5);

    print_all_clocks(&t0, &t1, &t2, &t3, &t4, &t5);
    return 0;
}
```

Cumulative time

```python
initialize()

for i in range(1000000):
    function_A()
    function_B()
    function_C()

cleanup()
```

```python
import time.time

initialize()
tA, tB, tC = 0

for i in range(1000000):
    t0 = time.time()
    function_A()

    t1 = time.time()
    function_B()

    t2 = time.time()
    function_C()

    t3 = time.time()

    tA += (t1 - t0)
    tB += (t2 - t1)
    tC += (t3 - t2)

cleanup()
```

Caveat: measuring time takes time!

`time.time()`: ~40 ns (and this value fluctuates!)

Microbenchmarks

What do we do if `function_A()` takes much less time than `time.time()`?

```
import time.time

initialize()
tA, tB, tC = 0

for i in range(1000000):
    t0 = time.time()
    function_A()

    t1 = time.time()
    function_B()

    t2 = time.time()
    function_C()

    t3 = time.time()

    tA = tA + (t1 - t0)
    tB = tB + (t2 - t1)
    tC = tC + (t3 - t2)

cleanup()
```

Microbenchmark for `function_A()`:

```
import time.time

initialize()

t0 = time.time()

for i in range(50000000):
    function_A()

t1 = time.time()

cleanup()
```

Microbenchmarks limitations

- It may not make sense to call `function_A()` in isolation
  - Take `sin(x)` for example: which value of x do we choose?
  - Always the same?
    - Are we sure `sin(0)` takes as much time as `sin(0.1)`?
  - A random value for x?
    - What if generating pseudo-random values takes more time than `sin()`?
- What about caches?
  - Caches will be “hot” (already filled with relevant data)
  - Microbenchmarking presents an over-optimistic picture of memory access times

Automated instrumentation: Profilers

gprof

Add "`-pg`" to `gcc/clang` parameters

```
gcc -O3 -o app app.c -pg
```

Run the application

```
./app
```

Generate report

```
gprof app
```

```
Flat profile:

Each sample counts as 0.01 seconds.
  %   cumulative   self              self     total
 time   seconds   seconds    calls   s/call   s/call  name
 63.77      3.82     3.82        1     3.82     4.24  tree_dfs
 28.88      5.55     1.73        1     1.73     1.73  lut_build
  4.17      5.80     0.25  1523737     0.00     0.00  aux_h_merge
  2.84      5.97     0.17    10331     0.00     0.00  aux_d_sort_swapper
  0.33      5.99     0.02                             tree_prune
  0.00      5.99     0.00     6715     0.00     0.00  aux_h_sort
  0.00      5.99     0.00      706     0.00     0.00  tree_gc
  0.00      5.99     0.00        6     0.00     0.00  dict_append_file
  0.00      5.99     0.00        1     0.00     0.00  dict_filter_dupes
  0.00      5.99     0.00        1     0.00     0.00  lut_hash_word
  0.00      5.99     0.00        1     0.00     0.00  solver_connected
  0.00      5.99     0.00        1     0.00     5.97  tree_build
```

- Pros
    - Easy to use
    - Exhaustive profile information
    - Generally low overhead
- Cons
    - Overhead increases when bottlenecks are in small, short functions (up to 2x runtime)
    - Limited accuracy

Hardware performance counters

The simplest hardware-aided performance-measuring tool is:

the time stamp counter (TSC)

- Introduced by Intel with the Pentium architecture (1993)
- Similar feature available on ARM since ARMv7 (1996)
- Special integer register
- Incremented by one at a constant rate (e.g. every clock cycle)
- Reading this register has high latency (>10 cycles)
- Useful for microbenchmarks and instrumentation
- `time.time() / clock_gettime()` use this internally

More complex performance counters

Since then, Intel and ARM have added many more performance counters:

- executed (“retired”) instructions
- branches
  - successfully predicted
  - mispredicted branches
- memory accesses
  - found in L1 cache
  - L1 misses, found in L2 cache
  - L2 misses, found in (last-level) L3 cache
  - L3 misses, found in main memory
  - TLB (page table cache) hits
  - TLB misses

- Pros
  - always measured
  - no performance penalty
  - no interference with normal execution

- Cons
  - only an aggregate measure (totals)

Linux perf

```
perf stat ./application
```

```
 Performance counter stats for './application':

          3,216.90 msec task-clock                       #    1.000 CPUs utilized
                 8      context-switches                 #    2.487 /sec
                 1      cpu-migrations                   #    0.311 /sec
             6,205      page-faults                      #    1.929 K/sec
     9,442,508,623      cycles                           #    2.935 GHz                         (52.90%)
     7,596,331,032      instructions                     #    0.80  insn per cycle              (58.81%)
     1,086,117,213      branches                         #  337.629 M/sec                       (58.84%)
         1,085,287      branch-misses                    #    0.10% of all branches             (58.87%)
     2,162,685,901      L1-dcache-loads                  #  672.289 M/sec                       (58.87%)
     1,079,393,101      L1-dcache-load-misses            #   49.91% of all L1-dcache accesses   (58.88%)
     1,069,062,732      LLC-loads                        #  332.327 M/sec                       (58.87%)
         6,537,301      LLC-load-misses                  #    0.61% of all L1-icache accesses   (23.50%)
     2,161,850,109      dTLB-loads                       #  672.029 M/sec                       (23.50%)
           896,301      dTLB-load-misses                 #    0.04% of all dTLB cache accesses  (23.50%)
         9,051,173      dTLB-stores                      #    2.814 M/sec                       (23.50%)
            81,624      dTLB-store-misses                #   25.374 K/sec                       (23.50%)

       3.217829387 seconds time elapsed

       3.167788000 seconds user
       0.022723000 seconds sys
```