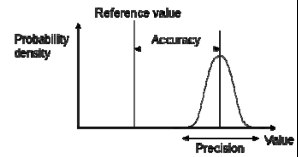
Measurements

General concepts

- Concepts that are often confused
- Repeatability vs. replicability
  - repeatability: repeating measurement on same setup gives more or less the same results
  - replicability: performing measurement on a different but similar setup gives more or less the same results
- Precision vs. accuracy
  - precision: how close are measurements to each other?
    - random error: remove by repeating measurement and taking average
  - accuracy: how close is measurement of a quantity to the actual value of that quantity (ground truth)?
    - systematic error



From: ~wiki/Accuracy_and_precision

Overview of lecture

- To understand and improve program performance, need insight into program behavior
  - execution time of program
  - how well program exploits hardware resources
    - memory hierarchy: cache hits and misses
    - processor pipeline: stalls
    - vector units
    - ….
- Measurements
  - basic ideas are quite simple
  - however processors are very complex so getting accurate measurements can be difficult
  - you must have a mental model of how processors execute instructions to make sensible measurements
- Libraries like PAPI simplify some measurements
- Intel Vtune gives you a deep look into program behavior but only on Intel processors

Timing your code

Basic idea

- Assume there is a way to get "current time" on the computer
  - for now, don't worry about precise definition of "current time"
- Timing your code
  - Use the pseudocode on right
- Problems
  - definition of "current time" can be quite subtle
  - modern computer systems are so complex that you may not be measuring what you think you are measuring
  - usually your code is written in C or some other high-level language and compiler may transform your code in unexpected ways
  - ….

```
tick = "getCurrentTime";

/*your code here */

tock = "getCurrentTime";

execTime = tock – tick;
```

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Main issues

1. Initial conditions matter
   - measured time may depend on state of machine when timing starts
2. Resolution and precision of timer
   - granularity of your measuring device
   - spread in measurements
3. Heisenberg effect
   - measurement may change quantity you are measuring
4. Compiler optimizations
   - may need to look at actual assembly code to make sure compiler has not modified your code in unexpected ways
5. Context-switching by O/S and hardware interrupts
   - you may end up measuring stuff outside your code
6. Out-of-order execution of instructions
   - what you measure may not be what you think you are measuring

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Main issues (1): Initial conditions

- Computers have a lot of internal state
  - caches, TLBs,…
- Internal state when measurement starts can affect execution time
  - are instructions in I-cache when measurement starts?
  - are memory locations accessed by your code in caches or in memory?
    - Fix: if you want to measure time starting with nothing in the cache, allocate a big array and walk over it to remove your data from cache in between runs

```
tick = "getCurrentTime";

/*your code here */        R

tock = "getCurrentTime";

execTime = tock – tick;
```

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Main issues(2): Resolution and precision

- Resolution:
  - how small a quantity can the device measure?
  - example: you can use a tape measure to measure cloth for a suit but not to measure how wide a hydrogen atom is
- If code in R is just a few instructions, your timer may not have resolution to measure this
  - what if timer only measured milliseconds?
  - what about overhead of getCurrentTime itself?
  - Fix: see next slide
- Precision:
  - assuming resolution is not a problem, how variable is the measurement?
  - if you repeat it ten times, how wide is the spread of measurements?
  - Fix: eliminate random error by repeating measurements and taking mean

```
tick = "getCurrentTime"

/*your code here */        R

tock = "getCurrentTime"

execTime = tock – tick
```

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Main issues(3): Heisenberg effect

- One solution to resolution problem:
  - put a loop around your code and execute it N times
  - divide (tock-tick) by N
- Problems:
  - loop code may change context of measurement
    - if loop counter i is allocated to a register, does that affect register allocation in your code?
    - are your instructions still in I-cache?
  - you are including loop overhead in your measurement

```
tick = "getCurrentTime"

/*your code here */

tock = "getCurrentTime"

execTime = tock – tick
```

```
tick = "getCurrentTime"
 for (int i=0;i<N;i++){
     /*your code here */
 }
tock = "getCurrentTime"

execTime = (tock – tick)/N
```

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Main issues(4): compiler optimizations

- Compiler can optimize your code in unexpected ways so you measure something different from what you are expected
- Example:
  - to eliminate effect of loop overhead in previous slide, you can try to measure execTime with and without your code in the loop body
  - however, compiler might optimize away the loop in the second piece of code since the loop body is empty
- Solutions
  - examine assembly code to ensure compiler is not changing code in unexpected ways
  - if it is, disable compiler optimizations (but this can change what you are measuring in undesirable ways)
  - you can tweak code to trick compiler to stop it from doing undesirable things

```
tick = "getCurrentTime";
 for (int i=0;i<N;i++){
     /*your code here */
 }
tock = "getCurrentTime";
execTime1 = (tock – tick);

tick = "getCurrentTime";
 for (int i=0;i<N;i++){
    /*empty loop body*/
}
tock = "getCurrentTime";
execTime2 = (tock – tick);

myCodeTime =
        (execTime1 – execTime2)/N;
```

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Main issues(5): Context-switching

- Code in R may not be executed in one shot by OS and processor
- OS may de-schedule your process while executing R, schedule code from other processes, and then get back to executing code from R
- This may happen many times during execution of R
- Analogy:
  - taking an exam vs. doing an assignment
- What is getCurrentTime measuring?
  - if it is elapsed time like "wall-clock time", process switches will confound your measurement
- Solutions:
  - disable process switches and interrupts before executing code in region (but you may not be able to do this in user mode)
  - find a timer that advances only when processor is executing your program
    - but context-switches may still pollute your caches

```
tick = "getCurrentTime"
                                  R
/*your code here */

tock = "getCurrentTime"

execTime = tock – tick
```

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Main issues(6): Out-of-order execution of instructions

- Modern processors execute instructions out of program order
  - but ensure dependences are satisfied
- Problem:
  - code from region R may get executed outside of tick and tock
  - code from outside region R may get executed between tick and tock
- Solution:
  - need to insert serializing instructions around region R
    - "fence off" instructions being timed from other instructions
  - similar to memory fences but for instructions of all types, not just memory operations

```
tick = "getCurrentTime"
                                  R
/*your code here */

tock = "getCurrentTime"

execTime = tock – tick
```

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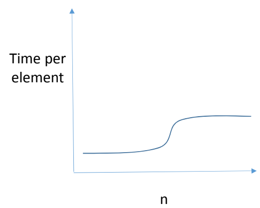
Example of measurement mistake

- Data structure
  - array, each element accessed once
  - little spatial locality
- Algorithm: O(n*log(n))
- Time per element
  - should be almost constant
  - yet pronounced jump at a particular array size
- Reason?



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Drilling down

- Key questions:
  - What can we use for “getCurrentTime” and what is its resolution?
  - How do we avoid timing errors from process-switches and interrupts?
  - How do we insert serialization instructions at tick and tock?
- Answer is very system-dependent but we will discuss three solutions for C/Linux/x86:
  - Linux call: clock_gettime
  - x86 code
  - PAPI counters

tick = “getCurrentTime”
/*your code here */
tock = “getCurrentTime”
execTime = tock – tick
R

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clock_gettime

```
#include <time.h>
struct timespec { time_t tv_sec; /* seconds */ long tv_nsec; /* nanoseconds */ };
int clock_gettime(clockid_t clk_id, struct timespec *tp)
int clock_getres (clockid_t clk_id, struct timespec *res)
```

- timespec
  - type for time measurement
  - two fields:
    - tv_sec (seconds)
    - tv_nsec (nanoseconds)
  - to get total time in nanoseconds, multiple tv_sec by a billion and add to tv_nsec
- clock_gettime
  - first argument: which clock?
  - some choices:
    - CLOCK_REALTIME: systemwide, real-time clock
    - CLOCK_PROCESS_CPUTIME_ID: high-resolution (nanosecond) timer for process
    - CLOCK_THREAD_CPUTIME_ID: high-resolution (nanosecond) timer for thread

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```
#include <stdio.h>  /* for printf */
#include <stdint.h> /* for uint64  */
#include <time.h>   /* for clock_gettime */

main(int argc, char **argv)
{   uint64_t execTime; /*time in nanoseconds */
    struct timespec tick, tock;

    clock_gettime(CLOCK_PROCESS_CPUTIME_ID, &tick);
       /* do stuff */
    clock_gettime(CLOCK_PROCESS_CPUTIME_ID, &tock);

    execTime = 1000000000 * (tock.tv_sec - tick.tv_sec) + tock.tv_nsec - tick.tv_nsec;
    printf("elapsed process CPU time = %llu nanoseconds\n", (long long unsigned int) execTime);
}
```

Implementation of clock_gettime should use serialization instructions.
CLOCK_PROCESS_CPUTIME_ID measures the amount of time spent in this process.
Resolution on systems I used is 1 nanosecond.
Even if /*do stuff */ is empty, execTime is about 2000 nanosec on these systems.

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x86 code

- Getting time:
  - TSC: 64-bit time-stamp counter that tracks cycles
  - RDTSC instruction: read time-stamp counter
    - EDX ← high-order 32 bits of counter
    - EAX ← low-order 32 bits of counter
    - no serialization guarantee
  - RDTSCP instruction
    - waits until all previous instructions have been executed before reading counter
    - however following instructions may begin execution before read is performed
- Serialization instruction:
  - CPUID instruction
    - modifies EAX, EBX, ECX, EDX registers
    - can be executed at any privilege level

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Further reading

- Linux man pages:
  - describes clock_gettime and other clocks
  - https://linux.die.net/man/3/clock_gettime
- Technical note from Intel:
  - shows how to use RDTSC and CPUID for accurate timing measurements
  - www.intel.com/content/dam/www/public/us/en/documents/white-papers/ia-32-ia-64-benchmark-code-execution-paper.pdf

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PAPI counters

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Hardware counters

- Modern CPUs have hardware counters for many events
  - Cycles
  - Instructions
  - Floating-point instructions
  - Loads and stores
  - I-cache misses
  - L1 data cache misses
  - L2 data cache misses
  - TLB misses
  - Pipeline stalls
  - .....
- Complications
  - accessing counters directly can be complex
  - code is not portable
  - on many processors, fewer hardware counters than events you can track so only a subset of events can be measured in a given run

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PAPI

- Performance Application Programming Interface
- Two interfaces to underlying counter hardware:
  - High-level interface: provides ability to start, stop and read counters for a specified list of events
  - Low-level interface: manages hardware events in user-defined groups called EventSets
- Timers and system information
- C and Fortran bindings
- PAPI interface to performance counters supported in the Linux 2.6.31 kernel
- User guide: http://icl.cs.utk.edu/projects/papi/files/documentation/PAPI_USER_GUIDE_23.htm

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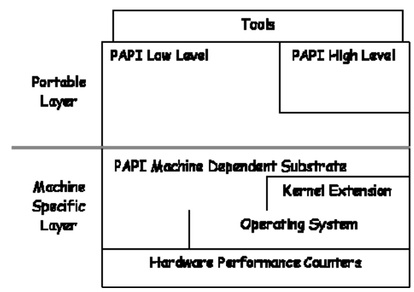
PAPI design



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PAPI Events

- Preset events
  - platform-independent names for events deemed useful for performance tuning
  - examples: accesses to the memory hierarchy, cache coherence protocol events, cycle and instruction counts, functional unit and pipeline utlilization
  - run PAPI papi_avail utility to determine preset events available on platform
- PAPI also provides access to native events through low-level interface
  - may be platform-specific

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PAPI preset events

- PAPI_L1_DCM: Level 1 data cache misses
- PAPI_L1_DCA: Level 1 data cache accesses
- PAPI_L1_ICM: Level 1 I-cache misses
- PAPI_L2_DCM: Level 2 data cache misses
- PAPI_L3_DCM: Level 3 data cache misses
- PAPI_FXU_IDL: cycles floating-point units are idle
- PAPI_TOT_INS: total instructions executed
- PAPI_TOT_CYC: total cycles
- PAPI_IPS: instructions executed per second
- .....

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PAPI_query_event

- Check whether CPU can measure the PAPI event you are interested in

```
if (PAPI_OK != PAPI_query_event(PAPI_TOT_INS))
                ehandler("Cannot count PAPI_TOT_INS.");

if (PAPI_OK != PAPI_query_event(PAPI_L1_DCM))
                ehandler("Cannot count PAPI_L1_DCM.");

if (PAPI_OK != PAPI_query_event(PAPI_L2_DCM))
                ehandler("Cannot count PAPI_L2_DCM.");
```

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High Level API

- Meant for application programmers wanting simple but accurate measurements
  - calls the lower level API
- Eight important functions:
  - PAPI_num_counters
    - how many hardware counters are supported?
  - PAPI_start_counters
  - PAPI_stop_counters
  - PAPI_read_counters
    - resets counters
  - PAPI_accum_counters
    - adds counters into accumulator array and zeroes them
  - PAPI_flops
    - floating-point operations per second
  - PAPI_flips
    - floating-point instructions per second
  - PAPI_ipc
    - instructions per cycle

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```
#include <stdlib.h>
#include <stdio.h>
#include <math.h>
#include <papi.h>

int main( int argc, char *argv[] ) {
        int i, j, k;

        long long counters[3];
        int PAPI_events[] = {
                PAPI_TOT_CYC,
                PAPI_L2_DCM,
                PAPI_L2_DCA };

        PAPI_library_init(PAPI_VER_CURRENT);

        i = PAPI_start_counters( PAPI_events, 3 );

        /* your code here */

        PAPI_read_counters( counters, 3 );

        printf("%lld L2 cache misses (%.3lf%% misses) in %lld cycles\n",
                counters[1],
                (double)counters[1] / (double)counters[2],
                counters[0] );

        return 0;
}
```

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Intel®VTune™ Amplifier

Basics for Timing

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Finding timings with Intel® VTune™ Amplifier

Advanced Hotspots Analysis collects clock-ticks and instructions retired

GUI or CLI Collections

```
> amplxe-cl -collect advanced-hotspots -- ./myapp.out
```

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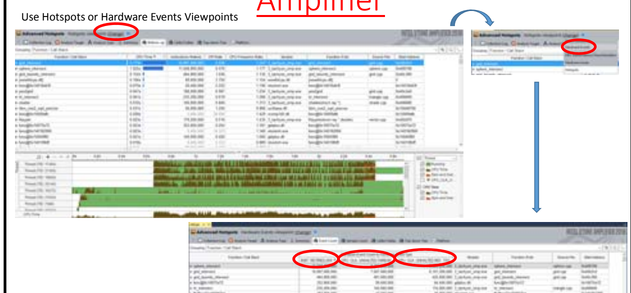
Finding timings with Intel® VTune™ Amplifier

Use Hotspots or Hardware Events Viewpoints



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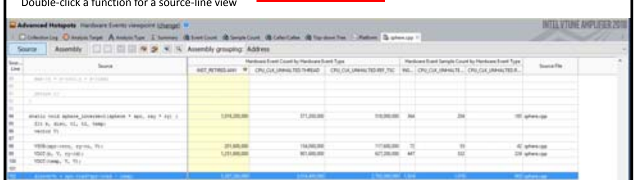
Finding timings with Intel® VTune™ Amplifier

Double-click a function for a source-line view



ITT APIs also allow collection control but are not required:
https://software.intel.com/en-us/vtune-amplifier-help-instrumentation-and-tracing-technology-apis

```
__itt_resume();
    while(gRunning) {
        doSomeDataParallelWork();
    }
__itt_pause();
```

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Summary

- Measurement
  - basic ideas are quite simple
  - however processors are very complex so getting accurate measurements can be difficult
- You must have a mental model of how processors execute instructions
- Libraries like PAPI simplify some measurements
- Intel VTune gives you an even deeper look into what your program is doing but only on Intel processors

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