# CSCE 488: Performance Evaluation

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## Why are We Here?

- Proper experimental technique is essential to system verification
- Without it, we're just hoping that everything works OK
- Here I'll focus on timing verification, but will also touch on functional verification
- Most work under UNIX, but certainly have NT counterparts

# UNIX `time` Command

Usage: `time <utility>`, where `utility` is any UNIX command with arguments

- Reports:
  - The elapsed (real) time between invocation of utility and its termination (includes I/O, other processes running, etc.)
  - The User CPU time: total time CPU spent running the program while in user mode
  - The System CPU time: total time CPU spent running the program while in kernel mode
- Total execution time is sum of user, system, (and I/O) ($\neq$ real time)
- Includes I/O instructions (not I/O itself), context switches, and any "preprocessing" of data (e.g. initializing arrays)
- NT version: `timethis` from NTresKit

## `time` Command Example

- Total (user + system) time for run A is 125 ms, total for run B is 140 ms $\Rightarrow$ B's run time is 12% longer

- But if context switches & preprocessing each take 100 ms, then B's run time really 60% longer

RULE 1: Make sure you're measuring the right thing

# More Precise Timing Measurements

- Use system calls around blocks of code to grab precise system timing info

- Times measured from arbitrary point in past (e.g. reboot) in number of “clock ticks”

- Can use to get time stamps at different points in the code and compute difference

E.g.

```
#include <sys/types.h>
#include <sys/times.h>

clock_t times(struct tms *buffer);
```

where

```
struct tms {
  clock_t tms_utime;   /* user time of current proc. */
  clock_t tms_stime;   /* system time of current proc. */
  clock_t tms_cutime;  /* child user time of current proc. */
  clock_t tms_cstime;  /* child sys. time of current proc. */
  };
```

- Can also use `clocks()` (ANSI C) or `times()` (SVr4, SVID, X/OPEN, BSD 4.3 and POSIX)

# ACE's Profile Timer

- Developed by Doug Schmidt in his ACE (Adaptive Communication Environment) package: `http://www.cs.wustl.edu/~schmidt/ACE.html`

- Timer is just a small part

- Gets up to (down to?) nanosecond precision (not nanosec. accuracy)

- Requires `sys/procfs.h` (not in NT?)

E.g.

```
main()
{
   Profile_Timer timer;
   Profile_Timer::Elapsed_Time et;

   timer.start();
  /* run code to be timed here */
   timer.stop();
   timer.elapsed_time(et);   /* compute elapsed time */
   cout << "time(in secs): " << et.user_time;
}
```

## Caveat

- Most system-independent timers are only updated every 10 ms
- Thus cannot rely on measurements more fine than that, even though they're available
- One approach: run same routine multiple times and take average
  - Can have problems with caches
  - Workaround: after every run, "flush" the cache, or use new dataset each time

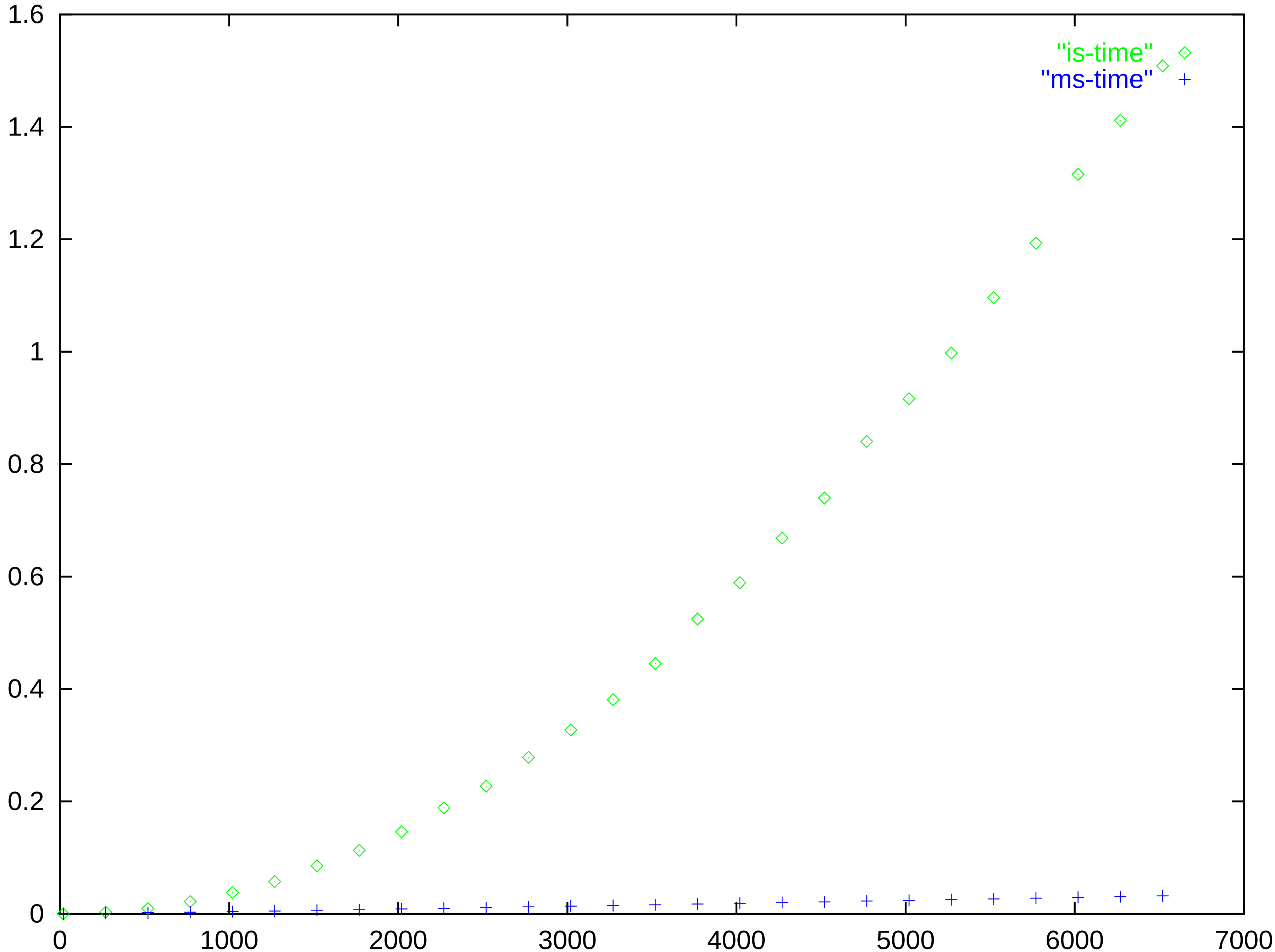
## Application of Timer
## Example: Merge Sort vs. Insertion Sort

- For sorting 20 items, IS took $2.0 \times 10^{-5}$ sec, made 363 comparisons

- For sorting 20 items, MS took $5.8 \times 10^{-5}$ sec, made 658 comparisons

- Conclusion: IS is more than twice as fast as MS [FALLACY]

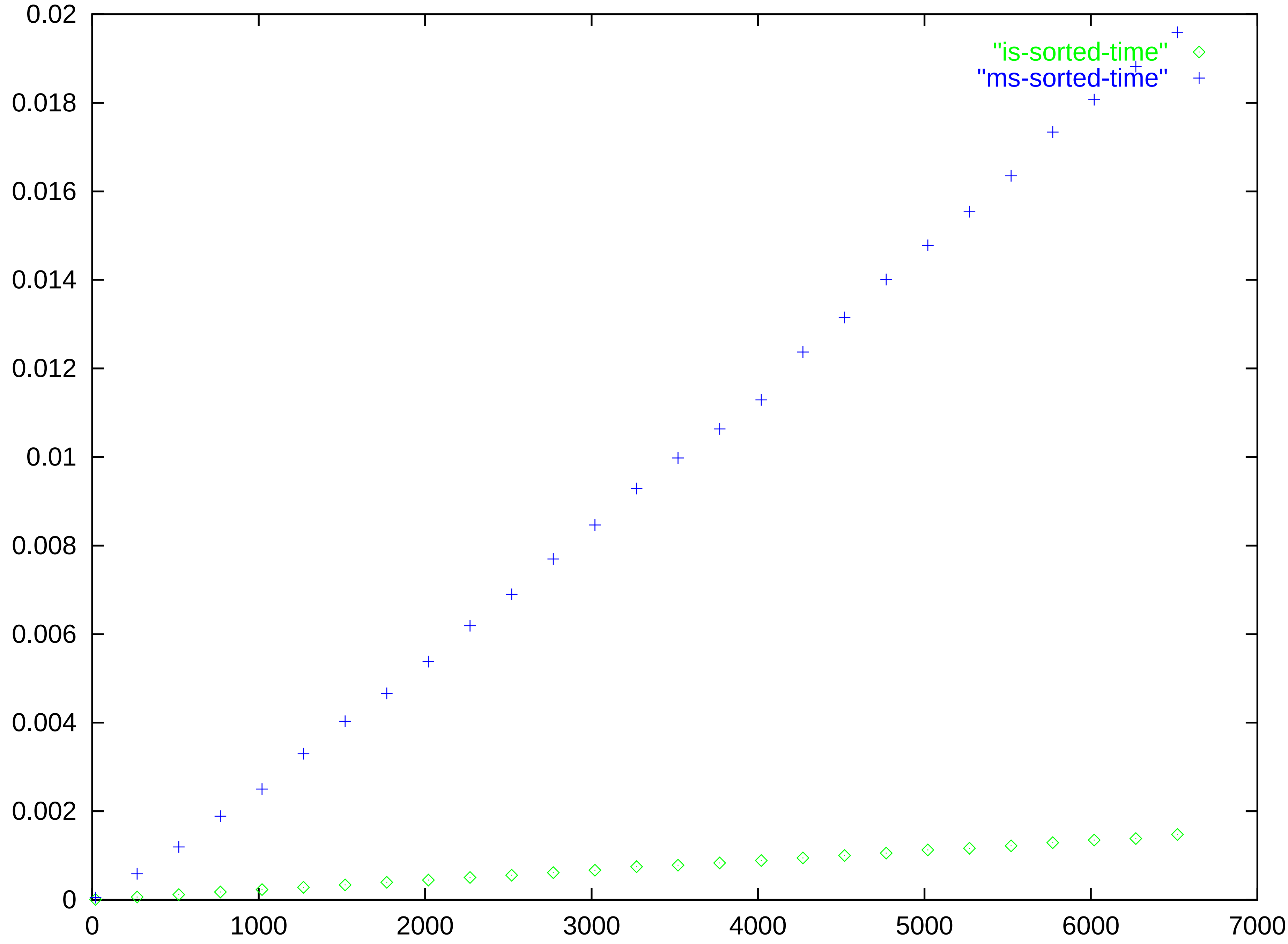
RULE 2: Measure trends


"is-time"
"ms-time"
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1000
2000
3000
4000
5000
6000
7000

## OK, Tough Guy, Let's Measure Trends

- Choose already sorted inputs to test the algorithm [INCORRECT TREND]

RULE 3: Take average over several inputs of the same size


"is-sorted-time"
"ms-sorted-time"
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
1000
2000
3000
4000
5000
6000
7000

## Sampling Theory

- What inputs should we use to test?

- Ideally, what you would see in practice
  - Don't always know this

- Next best thing: all possible inputs (exponentially or infinitely big) or a (uniformly) randomly selected set

- Rule of thumb: try at least 30 random sets and take mean

# Sampling Theory
(cont'd)

- Mean of $X_1, \ldots, X_m$ (e.g. sort times for $m$ inputs, each of size $n$): $\bar{X} = (1/m)\sum_{i=1}^{m} X_i$

- Standard deviation $s = \sqrt{\frac{\sum_{i=1}^{m}(X_i - \bar{X})^2}{m-1}}$
$= \sqrt{\frac{m(\sum_{i=1}^{m} X_i^2) - (\sum_{i=1}^{m} X_i)^2}{m(m-1)}}$ (compute on-line)

- If $m \geq 30$, we are 95% confident that the true mean is approximately in

$$\bar{X} \pm z_{0.025}(s/\sqrt{m}) = \bar{X} \pm 1.96(s/\sqrt{m}) \qquad (1)$$

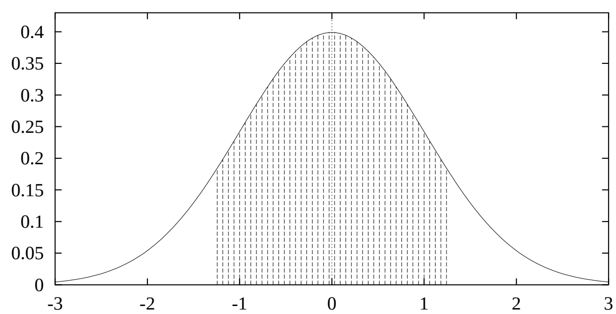
and we are 95% confident that the true mean is approximately at most

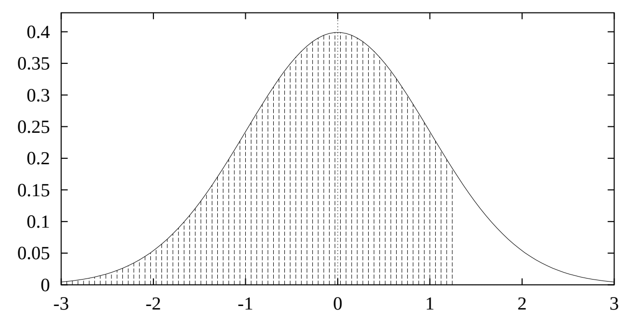
$$\bar{X} + z_{0.05}(s/\sqrt{m}) = \bar{X} + 1.645(s/\sqrt{m}) \qquad (2)$$

(1) is two-sided interval and (2) is one-sided

# Sampling Theory
(cont'd)

- Based on Central Limit Theorem, which states that regardless of the data's distribution, $\bar{X}$'s dist. is approximately Gaussian (normal) with variance $\approx s/\sqrt{m}$, assuming $m$ large enough




$N$% of area (probability) lies in $\mu \pm z_N \sigma$

| $N$% | 50% | 68% | 80% | 90% | 95% | 98% | 99% |
|---|---|---|---|---|---|---|---|
| $z_N$ | 0.67 | 1.00 | 1.28 | 1.64 | 1.96 | 2.33 | 2.58 |

$N$% of area lies $< \mu + z'_N \sigma$ or $> \mu - z'_N \sigma$, where $z'_N = z_{100-(100-N)/2}$

| $N$% | 50% | 68% | 80% | 90% | 95% | 98% | 99% |
|---|---|---|---|---|---|---|---|
| $z'_N$ | 0.0 | 0.47 | 0.84 | 1.28 | 1.64 | 2.05 | 2.33 |

Consult your Statistics text for more info, esp. on $z_\alpha$'s

## Hardware Timing

- Several CAD tools (incl. Xilinx Foundation) will perform timing analysis of designs after mapped to implementation technology
  - Make sure you use the right technology!
- An important aspect of this: critical path analysis, where the longest input-to-output path (in terms of time) is estimated and timed, which bounds the maximum clock rate
- Don't forget about e.g. printed circuit board delays, memory access latency, etc.
  - Take max delay between hardware and software components

# Functional Verification

- Hardware: CAD tools, e.g. Xilinx Foundation
- Software: run directly or use source-level debugger
- For both, test boundary and nominal conditions; go for high % cover of code/data paths
- When practicable, compare to hand simulation (e.g. with smaller inputs)
- HW/SW testing is active area of research (e.g. Prof. Elbaum)
- Formal methods: one approach used for verification of hw and sw designs, has been used on specific code sets/designs, not yet used in the large
- Extra problems occur with concurrency, e.g. multiple threads