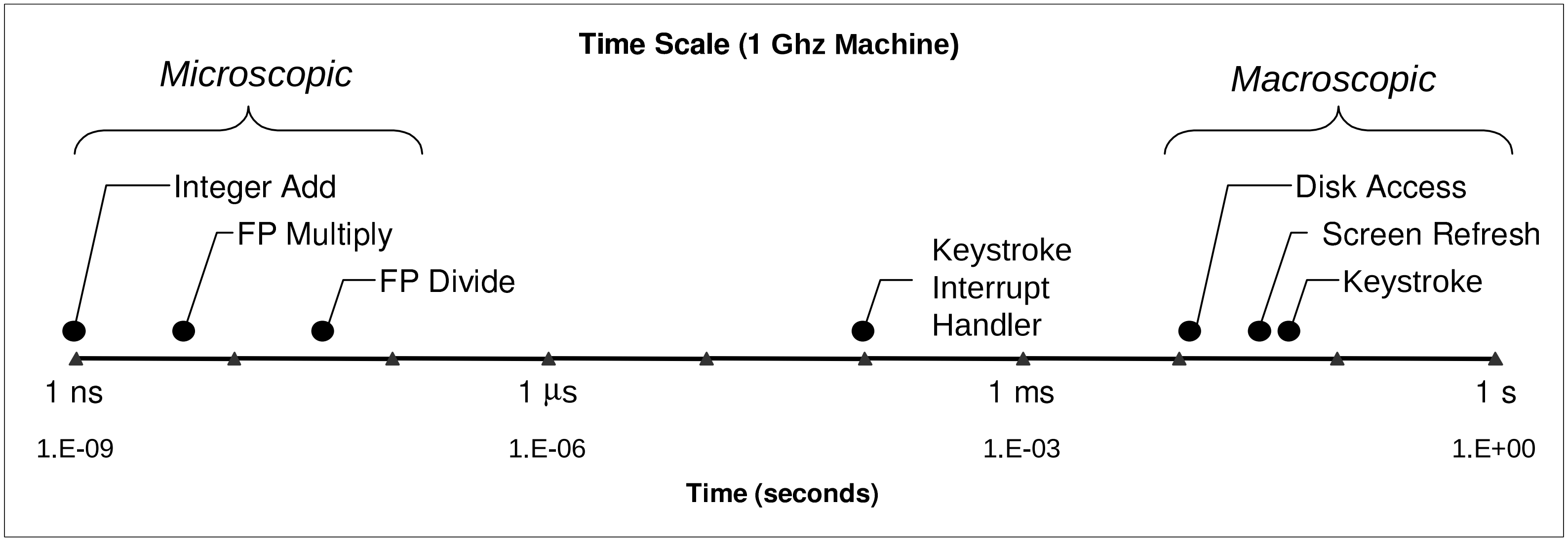
15-213

Time Measurement
October 25, 2001

Topics

- Time scales
- Interval counting
- Cycle counters
- K-best measurement scheme

Computer Time Scales



Two Fundamental Time Scales

- **Processor: $\sim 10^{-9}$ seconds**
- **External events: $\sim 10^{-2}$ seconds**
  - Keyboard input
  - Disk seek
  - Screen refresh

Implication

- **Can execute many instructions while waiting for external event to occur**
- **Can alternate among processes without anyone noticing**

Measurement Challenge

How Much Time Does Program X Require?

- **CPU time**
  - How many total seconds are used when executing X?
  - Measure used for most applications
  - Small dependence on other system activities
- **Actual (“Wall”) Time**
  - How many seconds elapse between the start and the completion of X?
  - Depends on system load, I/O times, etc.

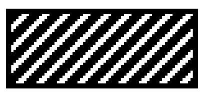
Confounding Factors

- **How does time get measured?**
- **Many processes share computing resources**
  - Transient effects when switching from one process to another
  - Suddenly, the effects of alternating among processes become noticeable

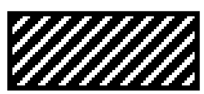
"Time" on a Computer System

real (wall clock) time

 = **user time** *(time executing instructing instructions in the user process)*

 = **system time** *(time executing instructing instructions in kernel on behalf of user process)*

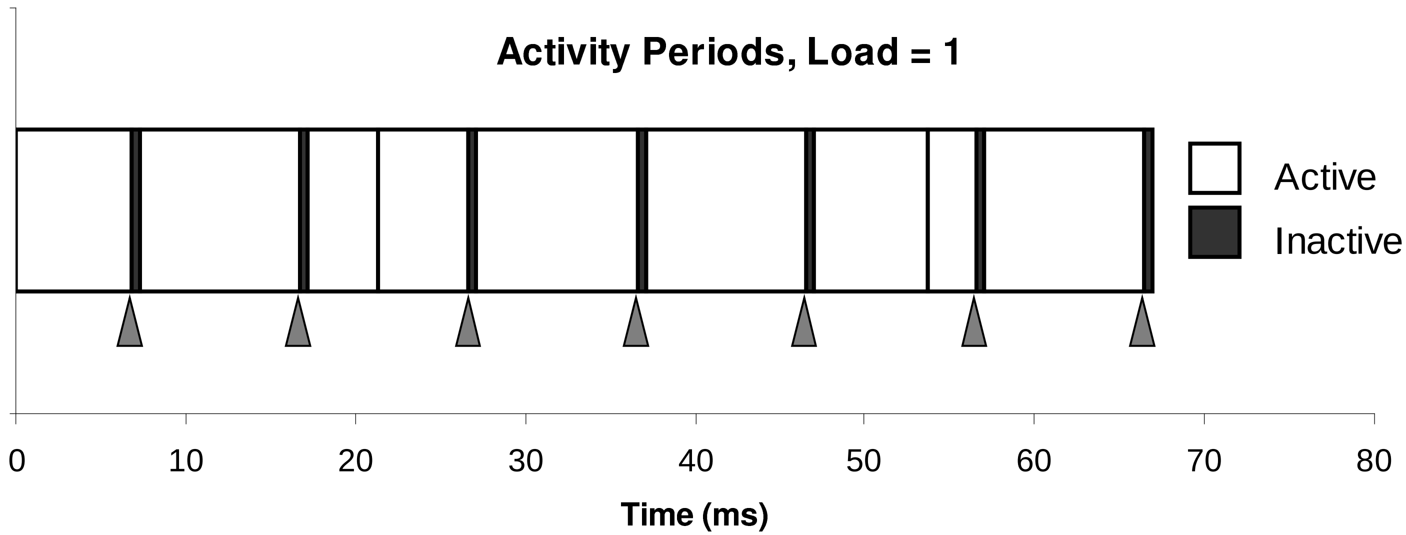
 = **some other user's time** *(time executing instructing instructions in different user's process)*

 +  +  = **real (wall clock) time**

We will use the word "time" to refer to user time.

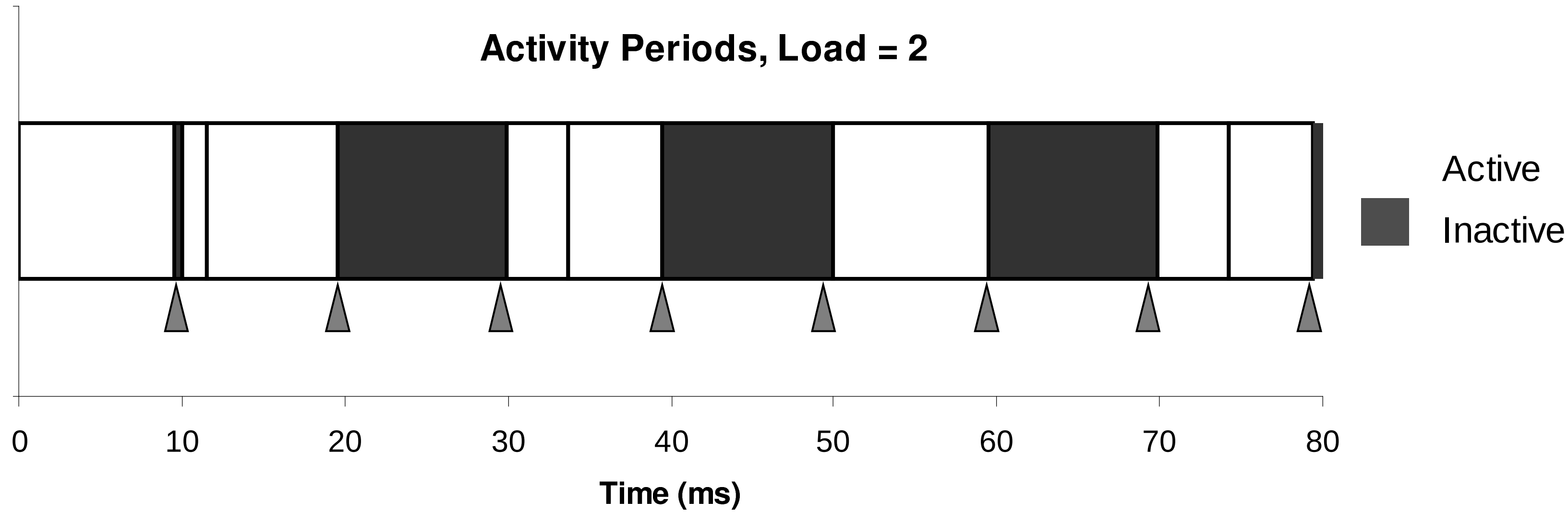
 **cummulative user time**

Activity Periods: Light Load



- **Most of the time spent executing one process**
- **Periodic interrupts every 10ms**
  - Interval timer
  - Keep system from executing one process to exclusion of others
- **Other interrupts**
  - Due to I/O activity
- **Inactivity periods**
  - System time spent processing interrupts
  - ~250,000 clock cycles

Activity Periods: Heavy Load



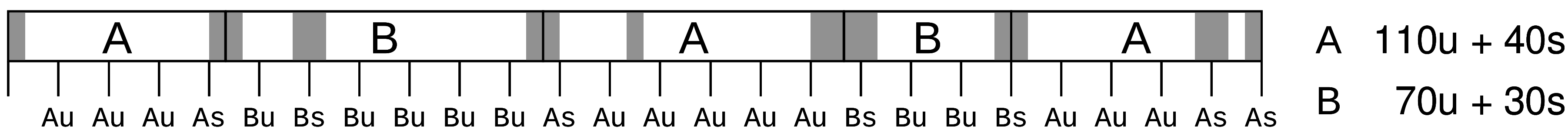
- **Sharing processor with one other active process**
- **Periodic interrupts every 10ms**
  - Interval timer
  - Keep system from executing one process to exclusion of others
- **Other interrupts**
  - Due to I/O activity
- **Inactivity periods**
  - System time spent processing interrupts
  - Periods when other process executes

Interval Counting

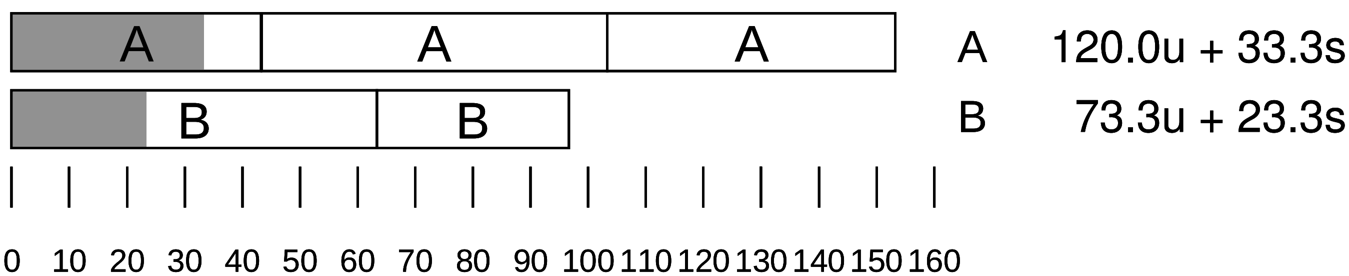
OS Measures Runtimes Using Interval Timer

- **Each time get timer interrupt, increment timer for executing process**
  - User time if running in user mode
  - System time if running in kernel mode

(a) Interval Timings



(b) Actual Times

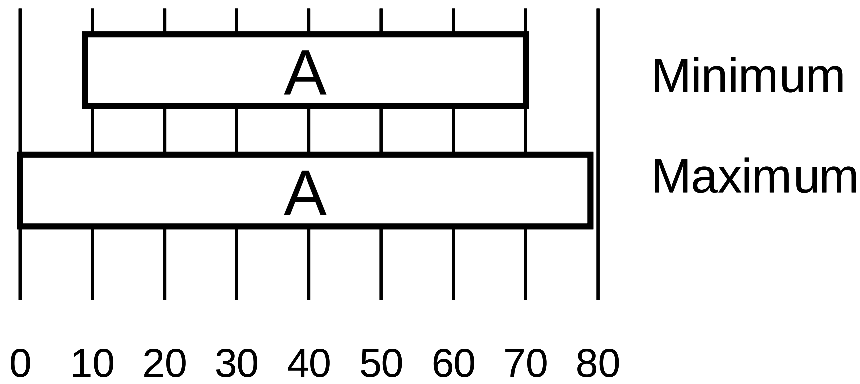


Unix `time` Command

```
time make osevent
gcc -O2 -Wall -g  -march=i486 -c clock.c
gcc -O2 -Wall -g  -march=i486 -c options.c
gcc -O2 -Wall -g  -march=i486 -c load.c
gcc -O2 -Wall -g  -march=i486 -o osevent osevent.c . . .
0.820u 0.300s 0:01.32 84.8%     0+0k 0+0io 4049pf+0w
```

- **0.82 seconds user time**
  - 82 timer intervals
- **0.30 seconds system time**
  - 30 timer intervals
- **1.32 seconds wall time**
- **84.8% of total was used running these processes**
  - (.82+0.3)/1.32 = .848

Accuracy of Interval Counting



- **Computed time = 70ms**
- **Min Actual = 60 + ε**
- **Max Actual = 80 – ε**

Worst Case Analysis

- **Timer Interval = δ**
- **Single process segment measurement can be off by $\pm\delta$**
- **No bound on error for multiple segments**
  - Could consistently underestimate, or consistently overestimate

Average Case Analysis

- **Over/underestimates tend to balance out**
- **As long as total run time is sufficiently large**
  - > 1 second
- **Consistently miss 4% overhead due to timer interrupts**

Cycle Counters

- **Most modern systems have built in registers that are incremented every clock cycle**
  - Very fine grained
  - Maintained as part of process state
    - » In Linux, counts elapsed global time
- **Special assembly code instruction to access**
- **On (recent model) Intel machines:**
  - 64 bit counter.
  - RDTSC instruction sets **`%edx`** to high order 32-bits, **`%eax`** to low order 32-bits

Wrap Around Times for 550 MHz machine

- **Low order 32-bits wrap around every 2^{32} / (550 * 10^6) = 7.8 seconds**
- **High order 64-bits wrap around every 2^{64} / (550 * 10^6) = 33539534679 seconds**
  - 1065.3 years

Measuring with Cycle Counter

Idea

- **Get current value of cycle counter**
  - store as pair of unsigned's `cyc_hi` and `cyc_lo`
- **Compute something**
- **Get new value of cycle counter**
- **Perform double precision subtraction to get elapsed cycles**

```
/* Keep track of most recent reading of cycle counter */
static unsigned cyc_hi = 0;
static unsigned cyc_lo = 0;

void start_counter()
{
  /* Get current value of cycle counter */
  access_counter(&cyc_hi, &cyc_lo);
}
```

Accessing the Cycle Counter (cont.)

- **GCC allows inline assembly code with mechanism for matching registers with program variables**
- **Code only works on x86 machine compiling with GCC**

```
void access_counter(unsigned *hi, unsigned *lo)
{
  /* Get cycle counter */
  asm("rdtsc; movl %%edx,%0; movl %%eax,%1"
      : "=r" (*hi), "=r" (*lo)
      : /* No input */
      : "%edx", "%eax");
}
```

- **Emit assembly with `rdtsc` and two `movl` instructions**
- **Code generates two outputs:**
  - **Symbolic register `%0`** should be used for **`*hi`**
  - **Symbolic register `%1`** should be used for **`*lo`**
- **Code has no inputs**
- **Registers `%eax` and `%edx` will be overwritten**

Completing Measurement

- **Get new value of cycle counter**
- **Perform double precision subtraction to get elapsed cycles**
- **Express as `double` to avoid overflow problems**

```
double get_counter()
{
  unsigned ncyc_hi, ncyc_lo
  unsigned hi, lo, borrow;
  /* Get cycle counter */
  access_counter(&ncyc_hi, &ncyc_lo);
  /* Do double precision subtraction */
  lo = ncyc_lo - cyc_lo;
  borrow = lo > ncyc_lo;
  hi = ncyc_hi - cyc_hi - borrow;
  return (double) hi * (1 << 30) * 4 + lo;
}
```

Timing With Cycle Counter

Determine Clock Rate of Processor

- Count number of cycles required for some fixed number of seconds

```
double MHZ;
int sleep_time = 10;
start_counter();
sleep(sleep_time);
MHZ = get_counter()/(sleep_time * 1e6);
```

Time Function P

- First attempt: Simply count cycles for one execution of P

```
double tsecs;
start_counter();
P();
tsecs = get_counter() / (MHZ * 1e6);
```

Timing with Cycle Counter

```
double MHZ;
int sleep_time = 10;
start_counter();
sleep(sleep_time);
MHZ = get_counter()/(sleep_time * 1e6);
```

```
double tsecs;
start_counter();
P();
tsecs = get_counter() / (MHZ * 1e6);
```

Measurement Pitfalls

Overhead

- Calling `get_counter()` incurs small amount of overhead
- Want to measure long enough code sequence to compensate

Unexpected Cache Effects

- artificial hits or misses
- e.g., these measurements were taken with the Alpha cycle counter:

```
foo1(array1, array2, array3);        /* 68,829 cycles */
foo2(array1, array2, array3);        /* 23,337 cycles */
```

vs.

```
foo2(array1, array2, array3);        /* 70,513 cycles */
foo1(array1, array2, array3);        /* 23,203 cycles */
```

Dealing with Overhead & Cache Effects

- **Always execute function once to “warm up” cache**
- **Keep doubling number of times execute P() until reach some threshold**
  - Used CMIN = 50000

```
int cnt = 1;
double cmeas = 0;
double cycles;
do  {
  int c = cnt;
  P();                    /* Warm up cache */
  get_counter();
  while (c-- > 0)
    P();
  cmeas = get_counter();
  cycles = cmeas / cnt;
  cnt += cnt;
} while (cmeas < CMIN);  /* Make sure have enough */
return cycles / (1e6 * MHZ);
```

Multitasking Effects

Cycle Counter Measures Elapsed Time

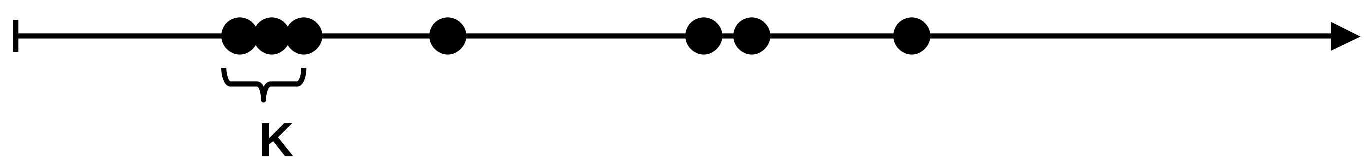
- **Keeps accumulating during periods of inactivity**
  - System activity
  - Running other processes

Key Observation

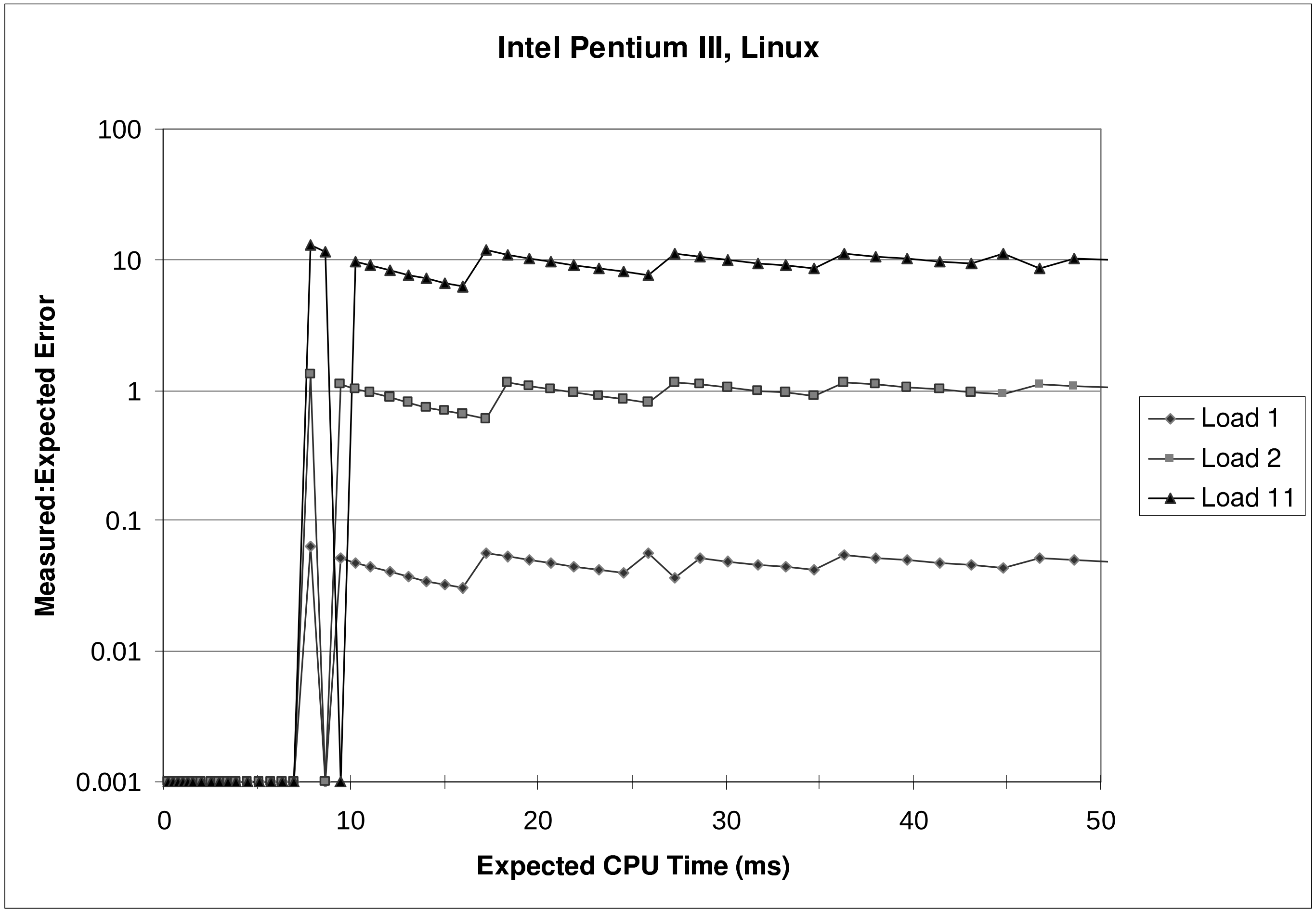
- **Cycle counter never underestimates program run time**
- **Possibly overestimates by large amount**

K-Best Measurement Scheme

- **Perform up to N (e.g., 20) measurements of function**
- **See if fastest K (e.g., 3) within some relative factor ε (e.g., 0.001)**



K-Best Validation



K = 3, ε = 0.001

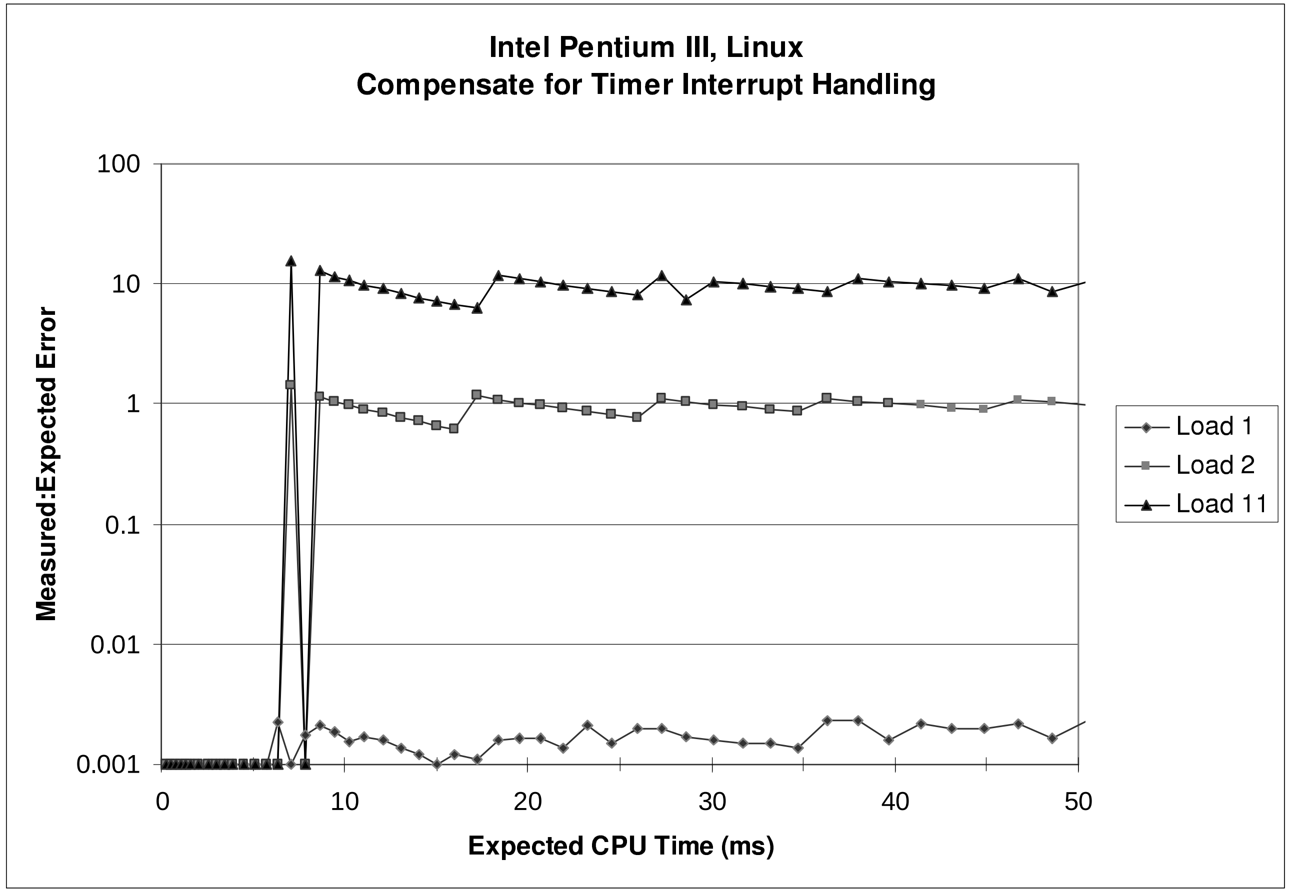
Very good accuracy for < 8ms

- **Within one timer interval**
- **Even when heavily loaded**

Less accurate of > 10ms

- **Light load: ~4% error**
  - Interval clock interrupt handling
- **Heavy load: Very high error**

Compensate For Timer Overhead



K = 3, ε = 0.001

Subtract Timer Overhead

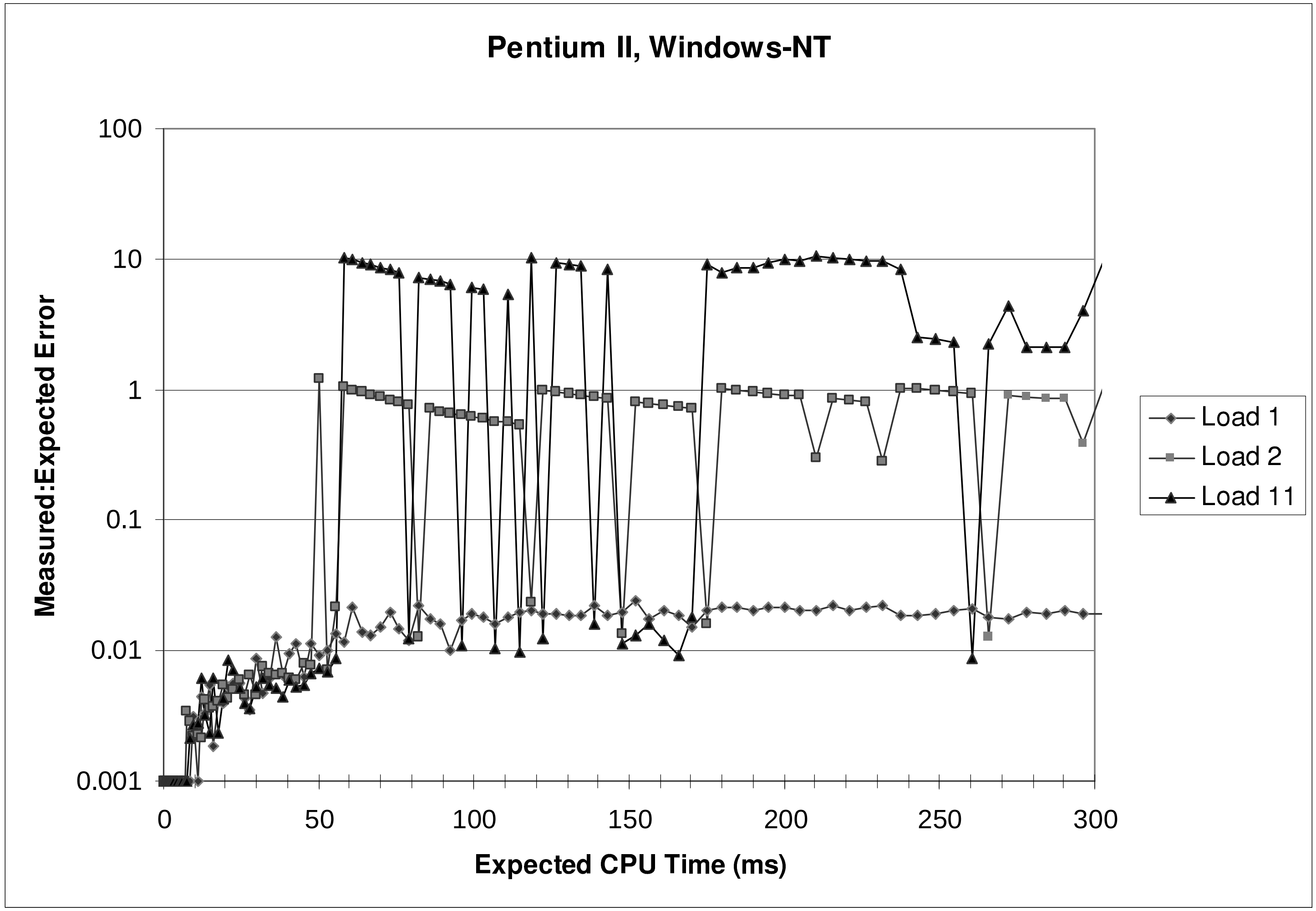
- Estimate overhead of single interrupt by measuring periods of inactivity
- Call interval timer to determine number of interrupts that have occurred

Better Accuracy for > 10ms

- Light load: 0.2% error
- Heavy load: Still very high error

K-Best on NT

$K = 3, \varepsilon = 0.001$



Acceptable accuracy for < 50ms

- Scheduler allows process to run multiple intervals

Less accurate of > 10ms

- Light load: 2% error
- Heavy load: Generally very high error

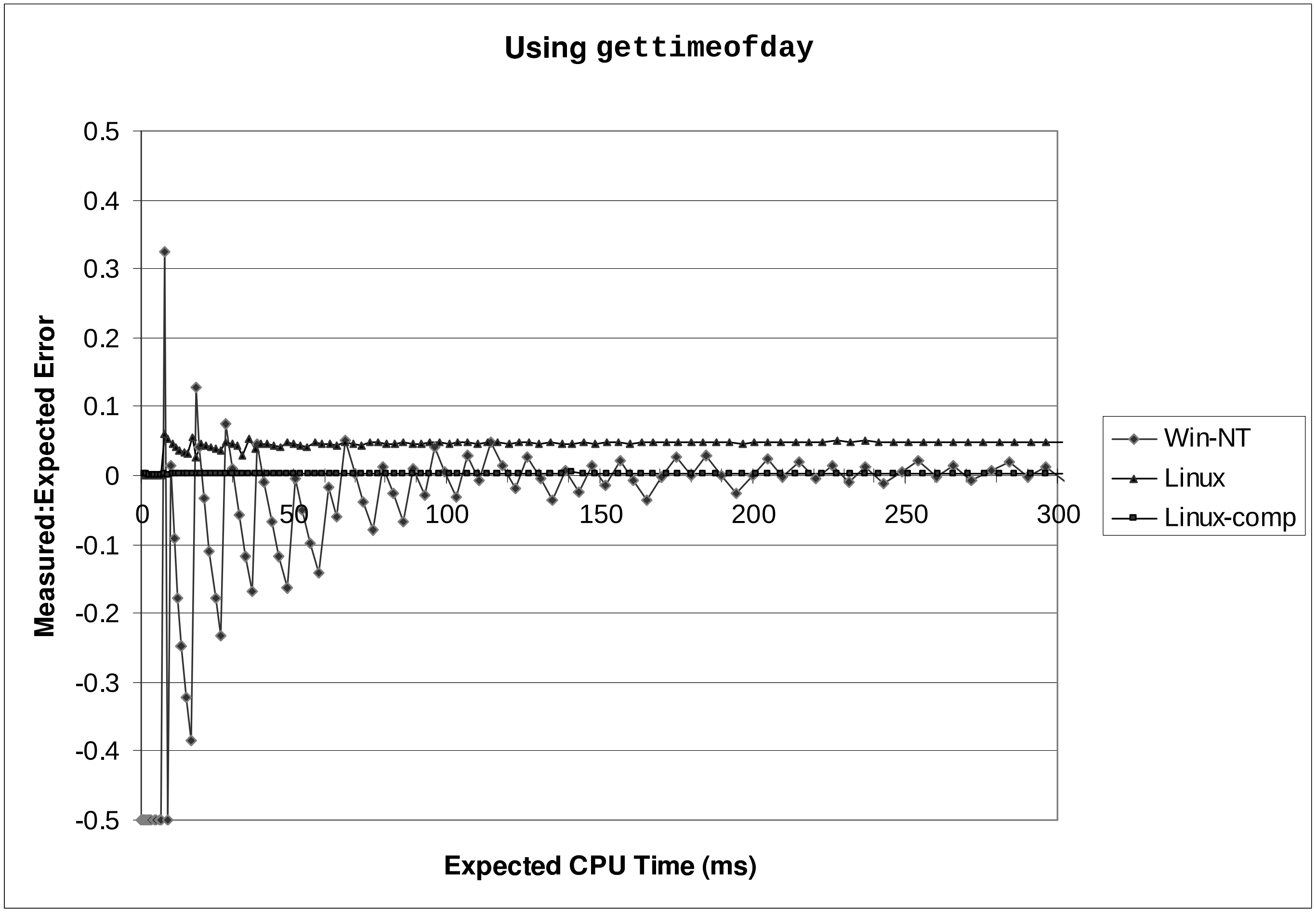
Time of Day Clock

- **Unix `gettimeofday()` function**
- **Return elapsed time since reference time (Jan 1, 1970)**
- **Implementation**
  - Uses interval counting on some machines
    - » Coarse grained
  - Uses cycle counter on others
    - » Fine grained, but significant overhead and only 1 microsecond resolution

```
#include <sys/time.h>
#include <unistd.h>

  struct timeval tstart, tfinish;
  double tsecs;
  gettimeofday(&tstart, NULL);
  P();
  gettimeofday(&tfinish, NULL);
  tsecs = (tfinish.tv_sec - tstart.tv_sec) +
      1e6 * (tfinish.tv_usec - tstart.tv_usec);
```

K-Best Using `gettimeofday`



Linux

- **As good as using cycle counter**
- **For times > 10 microseconds**

Windows

- **Implemented by interval counting**
- **Too coarse-grained**

Measurement Summary

Timing is highly case and system dependent

- **What is overall duration being measured?**
  - > 1 second: interval counting is OK
  - << 1 second: must use cycle counters
- **On what hardware / OS / OS version?**
  - Accessing counters
    - » How `gettimeofday` is implemented
  - Timer interrupt overhead
  - Scheduling policy

Devising a Measurement Method

- **Long durations: use Unix timing functions**
- **Short durations**
  - If possible, use gettimeofday
  - Otherwise must work with cycle counters
  - K-best scheme most successful