15-213

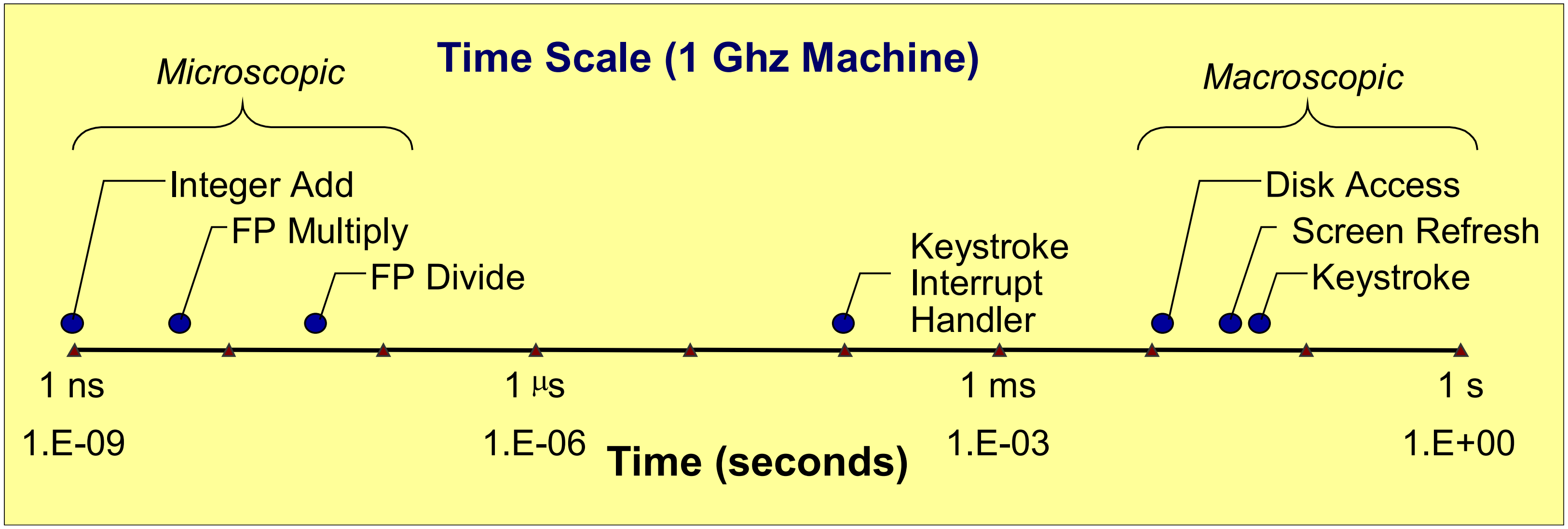
"The course that gives CMU its Zip!"

Time Measurement
December 9, 2004

Topics

- Time scales
- Interval counting
- Cycle counters
- K-best measurement scheme
- Related tools & ideas

Computer Time Scales



Two Fundamental Time Scales

- Processor: ~10^{-9} sec.
- External events: ~10^{-2} sec.
  - 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

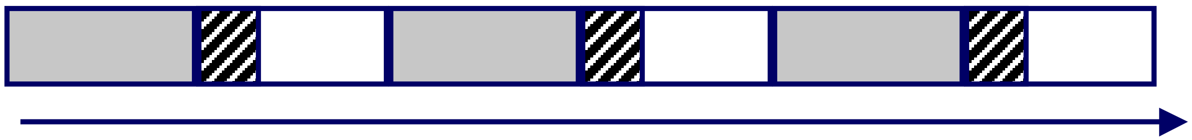
How Much Time Does Program X Require?

- 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

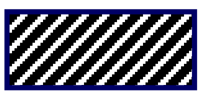
- How does time get measured?
- Many processes share computing resources
  - Transient effects when switching from one process to another
  - Suddenly, the effects of alternating among processes become noticeable

"Time" on a Computer System

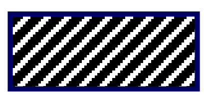


real (wall clock) time

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

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

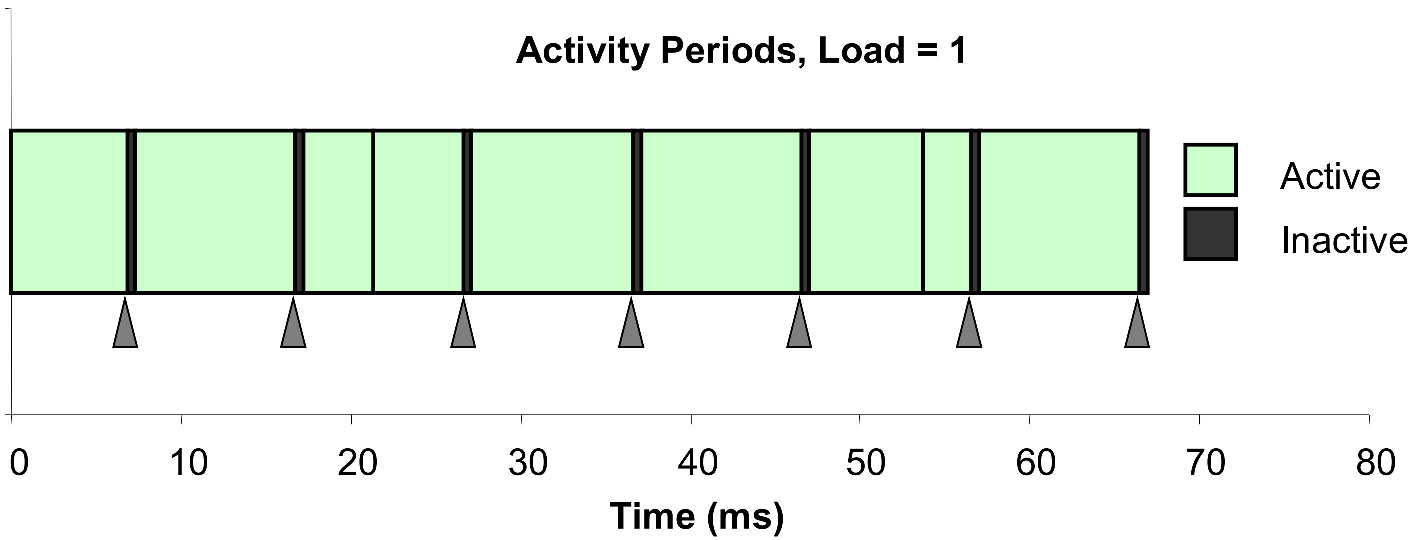
 **= some other user's time** *(time executing instructions in different user's process)*

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

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

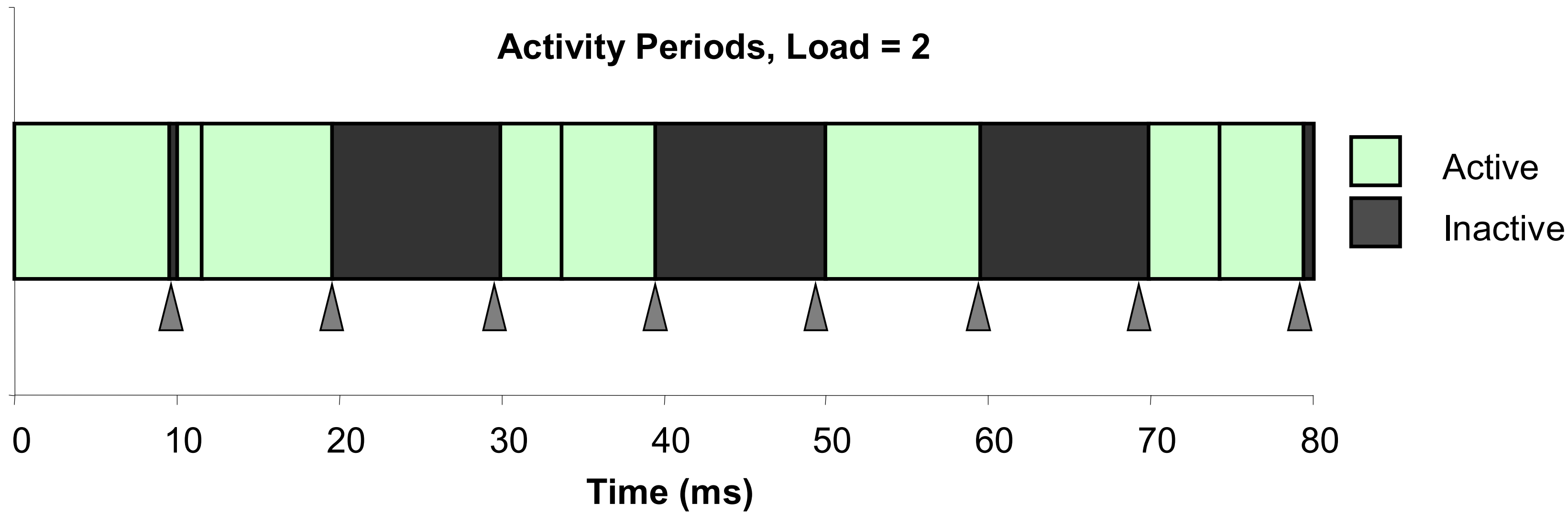
 **cumulative user time**

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
- From perspective of this process, system appears to be "inactive" for ~50% of the time
  - Other process is executing

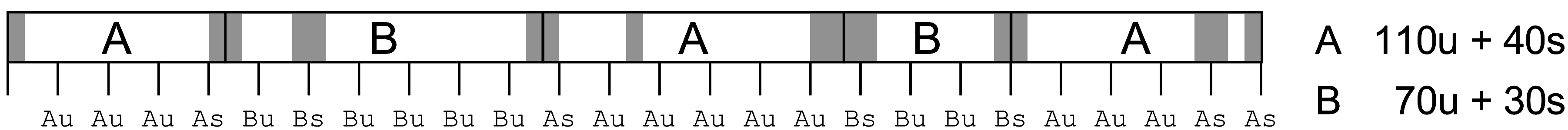
Interval Counting

OS Measures Runtimes Using Interval Timer

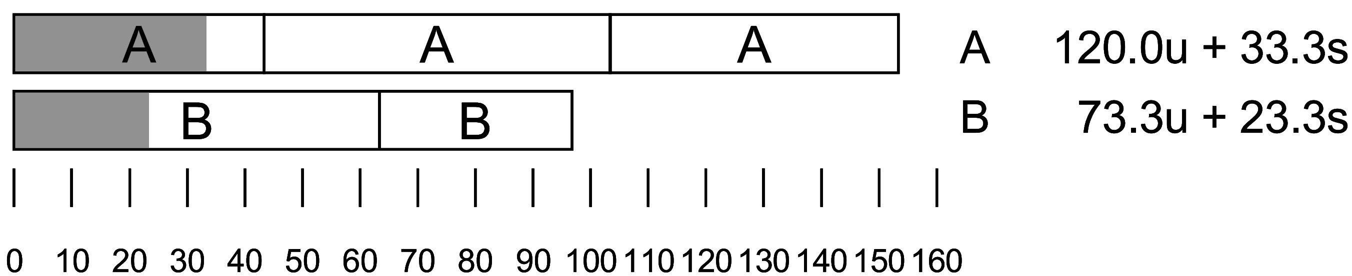
- Maintain 2 counts per process
  - User time
  - System time
- Each time get timer interrupt, increment counter for executing process
  - User time if running in user mode
  - System time if running in kernel mode

Interval Counting Example

(a) Interval Timings



(b) Actual Times

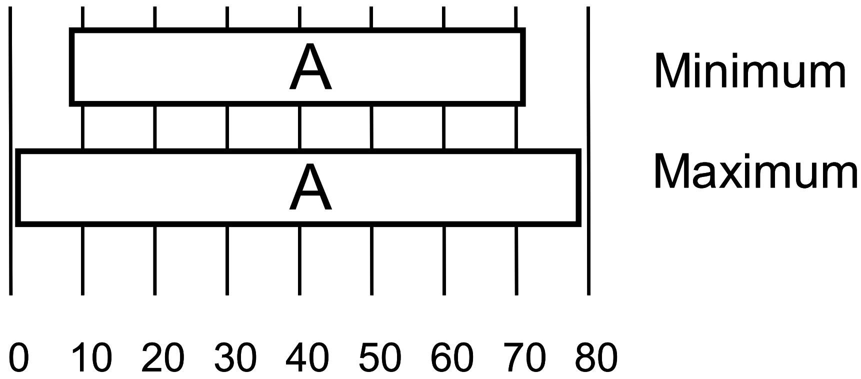


Unix `time` Command

```
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

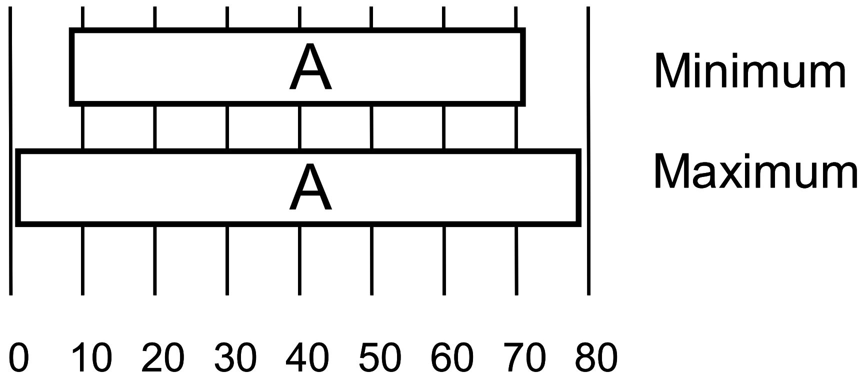


- Computed time = 70ms
- Min Actual = 60 + ε
- Max Actual = 80 – ε

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

Accuracy of Interval Couting (cont.)



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

Average Case Analysis

- Over/underestimates tend to balance out
- As long as total run time is sufficiently large
  - Min run time ~1 second
  - 100 timer intervals
- 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

- Aside: Is this a security issue?

Cycle Counter Period

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 years

For 2 GHz machine

- Low order 32-bits every 2.1 seconds
- High order 64 bits every 293 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 Cntr.

- 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

Closer Look at Extended ASM

```
asm("Instruction String"
       : Output List
       : Input List
       : Clobbers List);
}
```

```
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");
}
```

Instruction String

- Series of assembly commands
  - Separated by "`;`" or "`\n`"
  - Use "`%%`" where normally would use "`%`"

Closer Look at Extended ASM

```
asm("Instruction String"
       : Output List
       : Input List
       : Clobbers L
}
```

```
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");
}
```

Output List

- Expressions indicating destinations for values `%0`, `%1`, …, `%j`
  - Enclosed in parentheses
  - Must be *lvalue*
    - » Value that can appear on LHS of assignment
- Tag `"=r"` indicates that symbolic value (`%0`, etc.), should be replaced by a register

Closer Look at Extended ASM

```
asm("Instruction String"
      : Output List
      : Input List
      : Clobbers L
}
```

```
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");
}
```

Input List

- Series of expressions indicating sources for values `%j+1`, `%j+2`, …
  - Enclosed in parentheses
  - Any expression returning value
- Tag `"r"` indicates that symbolic value (`%0`, etc.) will come from register

Closer Look at Extended ASM

```
asm("Instruction String"
      : Output List
      : Input List
      : Clobbers I
}
```

```
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");
}
```

Clobbers List

- List of register names that get altered by assembly instruction
- Compiler will make sure doesn't store something in one of these registers that must be preserved across `asm`
  - Value set before & used after

Accessing the Cycle Cntr. (cont.)

Emitted Assembly Code

```
        movl 8(%ebp),%esi      # hi
        movl 12(%ebp),%edi     # lo
#APP
        rdtsc; movl %edx,%ecx; movl %eax,%ebx
#NO_APP
        movl %ecx,(%esi)       # Store high bits at *hi
        movl %ebx,(%edi)       # Store low bits at *lo
```

- Used `%ecx` for `*hi` (replacing `%0`)
- Used `%ebx` for `*lo` (replacing `%1`)
- Does not use `%eax` or `%edx` for value that must be carried across inserted assembly code

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);
```

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

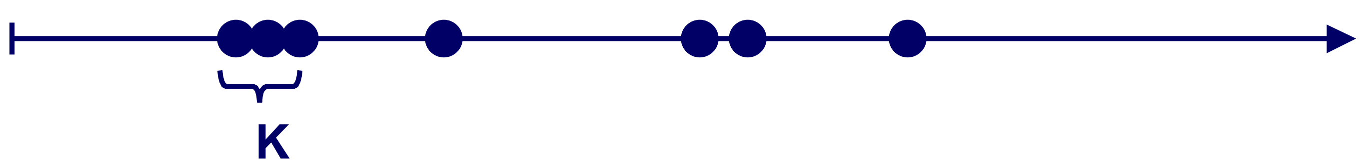
- Keeps accumulating during periods of inactivity
  - System activity
  - Running other processes

Key Observation

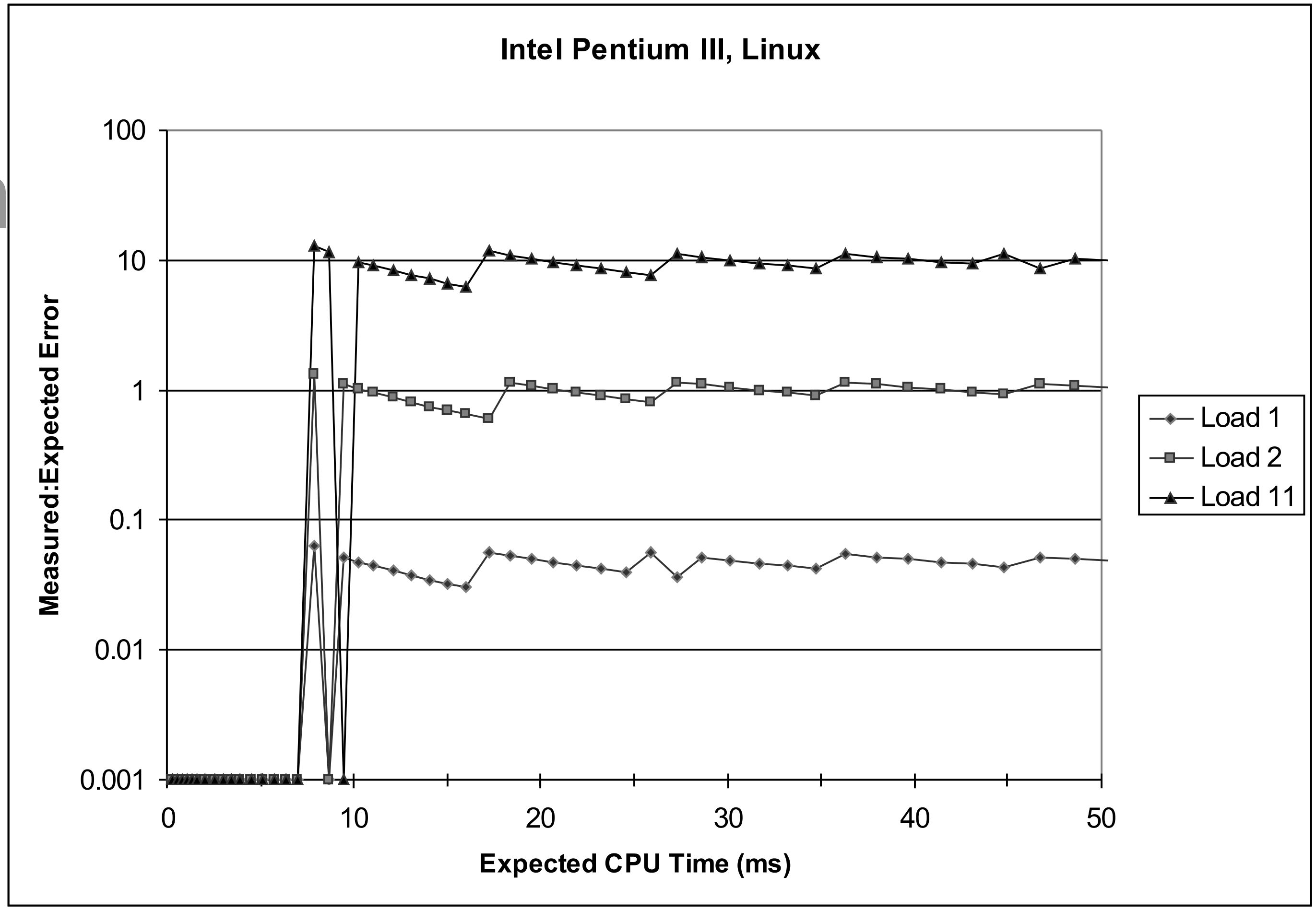
- Cycle counter never underestimates program run time
- Possibly overestimates by large amount

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

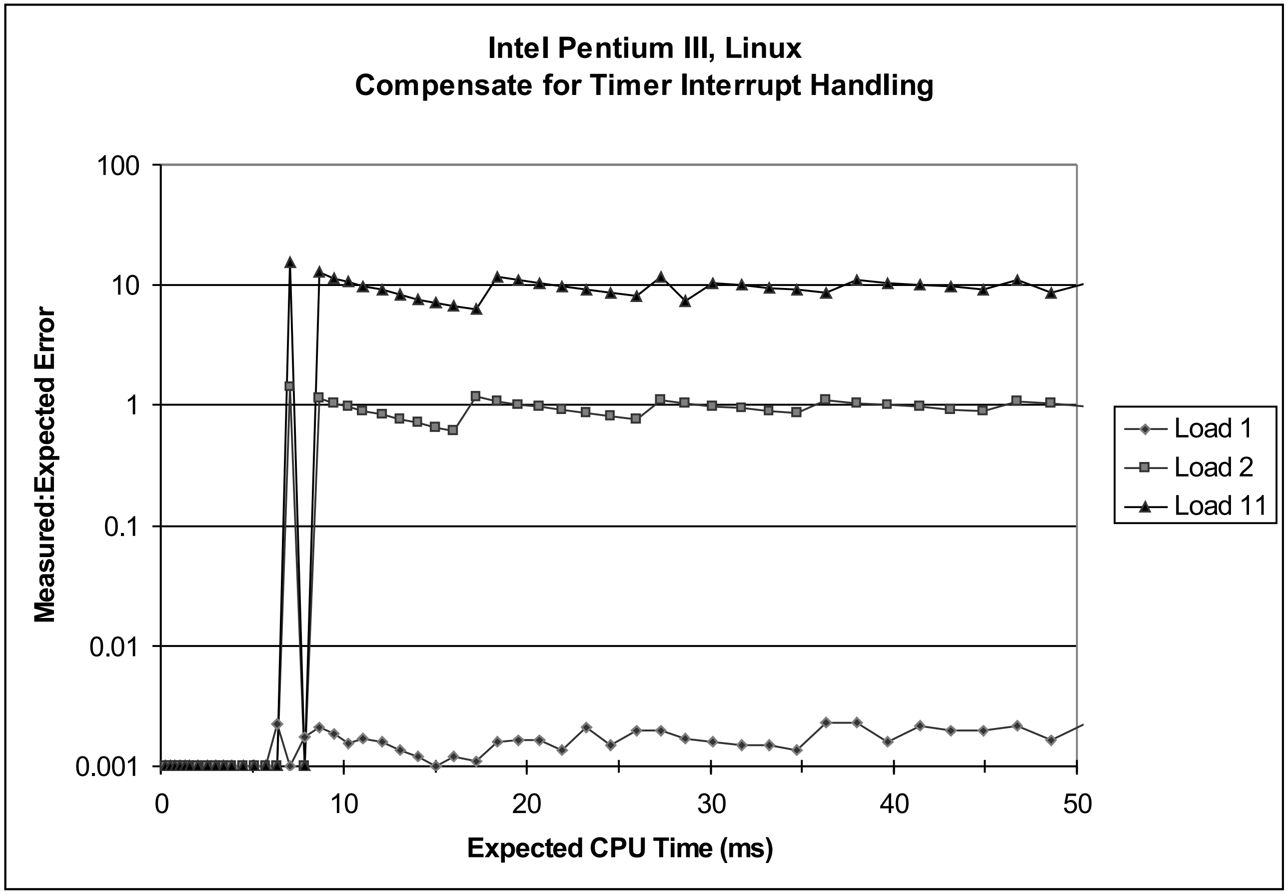
Very good accuracy for < 8ms

- 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

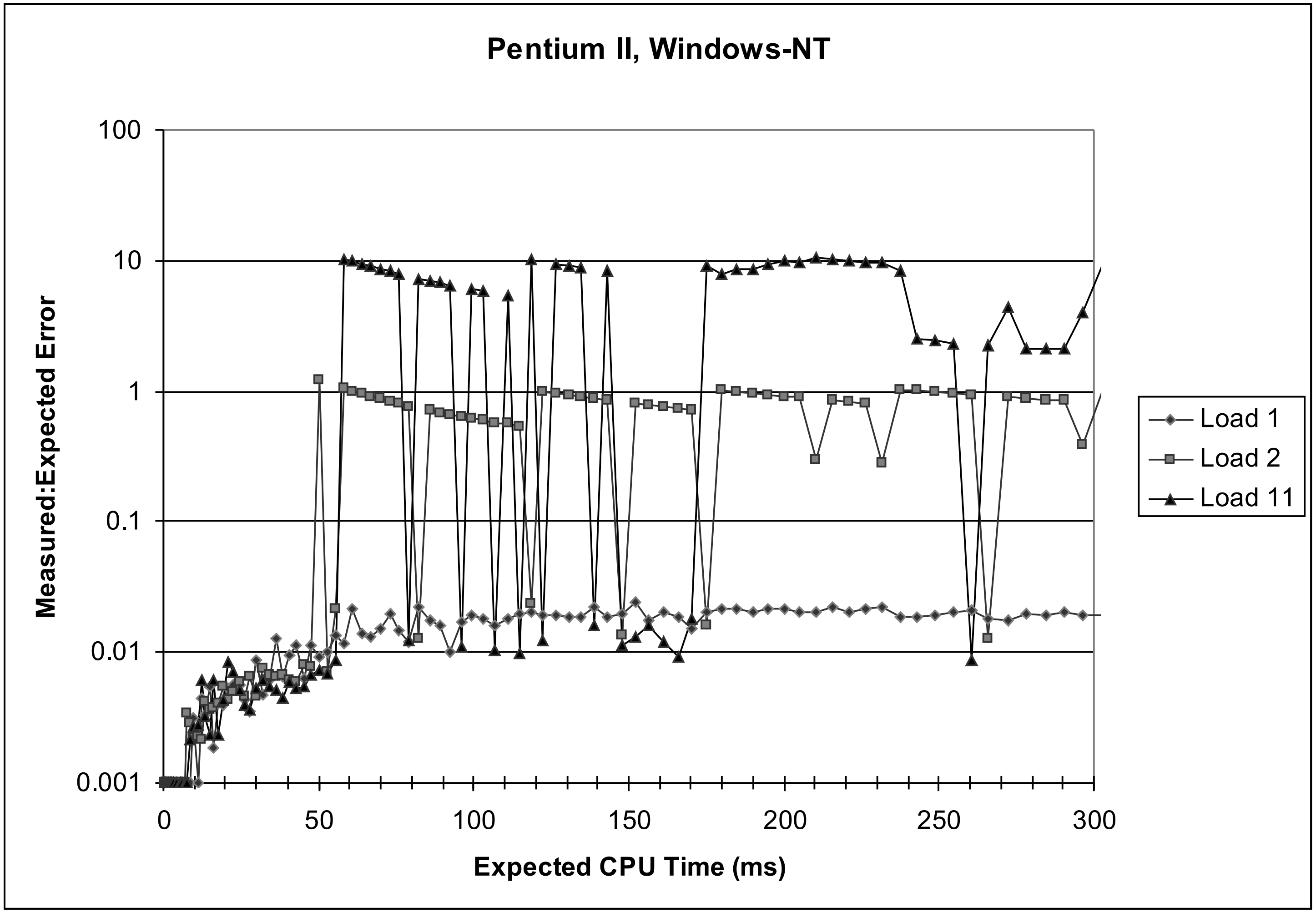
- Estimate overhead of single interrupt by measuring periods of inactivity
- Call interval timer to determine number of interrupts that have occurred

Better Accuracy for > 10ms

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

K-Best on NT

K = 3, ε = 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

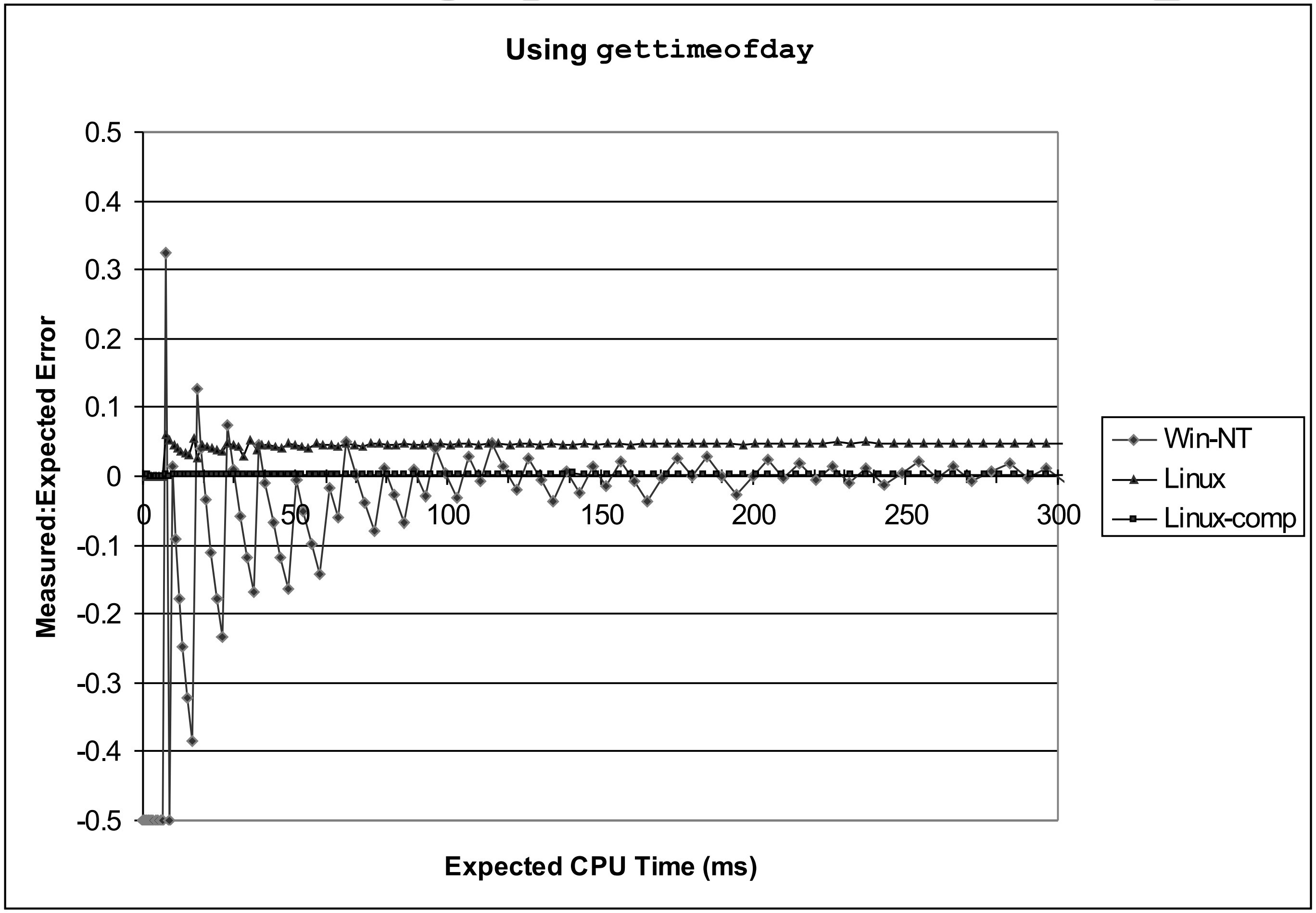
Time of Day Clock

- 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

Profiling a Program

```
Gcc -gp -o foo foo.c
./foo
Gprof gmon.out
```

How does this work?

- Samples PC periodically
- Adds code to count function calls
- Computes call-graph to attribute time

Limitations?

- High error for very short functions
- Adds overhead to collect and save profile data
- Does not profile system calls
- Cannot deal with multiple processes
- Gets confused by multiple threads
- Needs special compilation (or at least linking)

Uses:

- Identify targets for optimization

Digital's (RIP) Continuous Profiling Infrastructure

Primary idea: statistically sample PC all the time

Attibute PC samples to basic blocks and use flow analysis on the static program execution graph

Benefit:

- **Profiles everything all the time without need for modification of the executable image**
- **Low overhead (1-3%)**
- **Attributes dynamic cycles to individual instructions of the source program**

Reference:

"Continuous Profiling: Where Have All the Cycles Gone?", **J.M.Anderson,et.al, ASPLOS'97**