

15-213

"The course that gives CMU its Zip!"

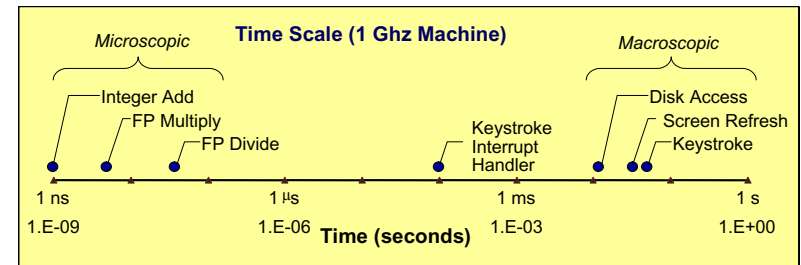
Time Measurement Apr. 8, 2003

Topics

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

class22.ppt

Computer Time Scales



Two Fundamental Time Scales Implication

- Processor: $\sim 10^{-9}$ sec.
- External events: $\sim 10^{-2}$ sec.
 - Keyboard input
 - Disk seek
 - Screen refresh
- Can execute many instructions while waiting for external event to occur
- Can alternate among processes without anyone noticing

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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

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"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)

$$\text{gray box} + \text{hatched box} + \text{white box} = \text{real (wall clock) time}$$

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

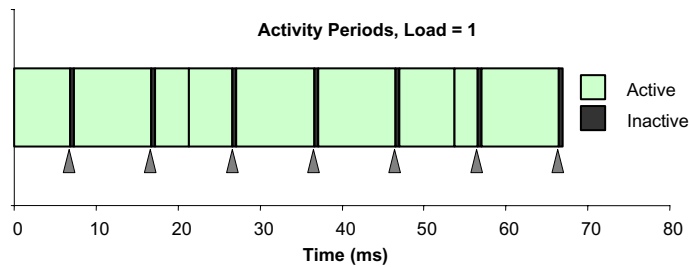


cumulative user time

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Activity Periods: Light Load

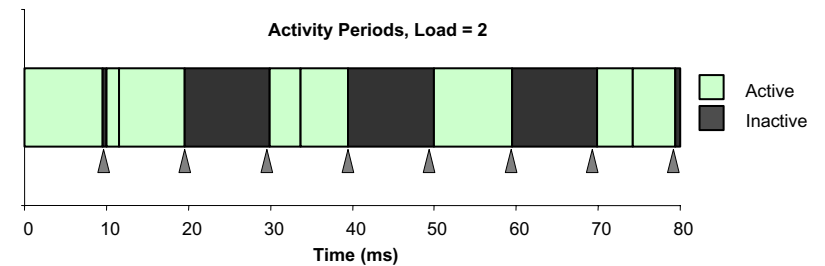


- Most of the time spent executing one process
- Periodic interrupts every 10ms
 - Interval timer
 - Keep system from executing one process to exclusion of others
- Other interrupts
 - Due to I/O activity
- Inactivity periods
 - System time spent processing interrupts
 - ~250,000 clock cycles

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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

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Interval Counting

OS Measures Runtimes Using Interval Timer

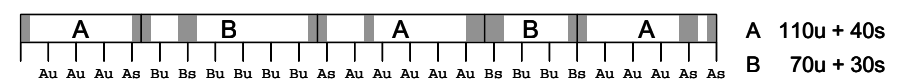
- Maintain 2 counts per process
 - User time
 - System time
- Each time get timer interrupt, increment counter for executing process
 - User time if running in user mode
 - System time if running in kernel mode

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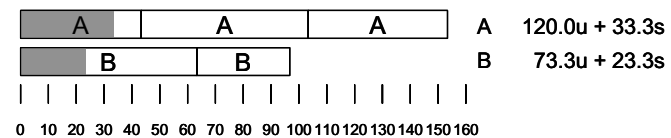
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Interval Counting Example

(a) Interval Timings



(b) Actual Times



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Unix time Command

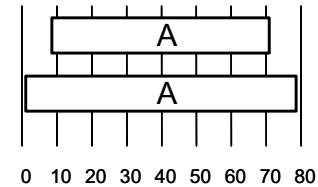
```
time make osevent
gcc -O2 -Wall -g -march=i486 -c clock.c
gcc -O2 -Wall -g -march=i486 -c options.c
gcc -O2 -Wall -g -march=i486 -c load.c
gcc -O2 -Wall -g -march=i486 -o osevent osevent.c . . .
0.820u 0.300s 0:01.32 84.8% 0+0k 0+0io 4049pf+0w
```

- 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
 - $(.82+0.3)/1.32 = .848$

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Accuracy of Interval Counting



Minimum

Maximum

- Computed time = 70ms
- Min Actual = $60 + \epsilon$
- Max Actual = $80 - \epsilon$

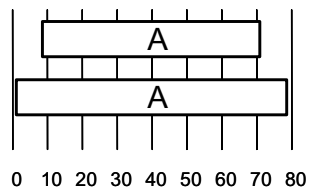
Worst Case Analysis

- 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

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Accuracy of Int. Cntg. (cont.)



Minimum

Maximum

- Computed time = 70ms
- Min Actual = $60 + \epsilon$
- Max Actual = $80 - \epsilon$

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

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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

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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 void access_counter
    : Clobbers I (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 register

Closer Look at Extended ASM

```
asm("Instruction String"
    : Output List
    : Input List void access_counter
    : Clobbers I (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 void access_counter
    : Clobbers I (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 ncyk_hi, ncyk_lo
    unsigned hi, lo, borrow;
    /* Get cycle counter */
    access_counter(&ncyk_hi, &ncyk_lo);
    /* Do double precision subtraction */
    lo = ncyk_lo - cyc_lo;
    borrow = lo > ncyk_lo;
    hi = ncyk_hi - cyc_hi - borrow;
    return (double) hi * (1 << 30) * 4 + lo;
}
```

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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);
```

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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 */

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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);
```

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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

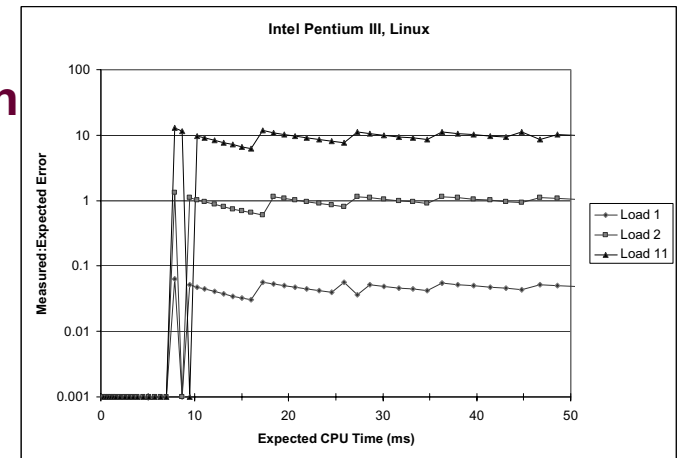
K-Best Measurement Scheme

- 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

$K = 3, \epsilon = 0.001$



Very good accuracy for < 8ms

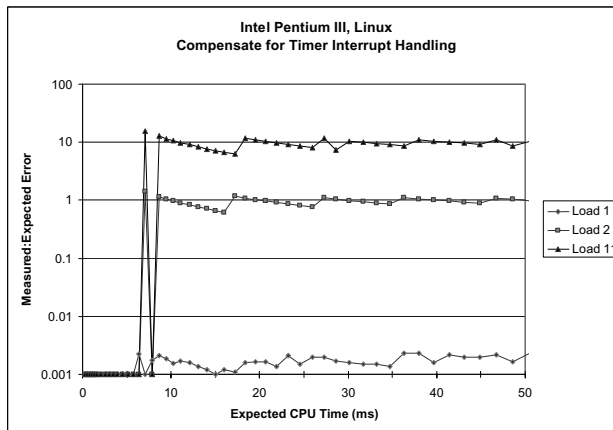
- Within one timer interval
- Even when heavily loaded

Less accurate of > 10ms

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

Compensate For Timer Overhead

$K = 3, \epsilon = 0.001$



Subtract Timer Overhead

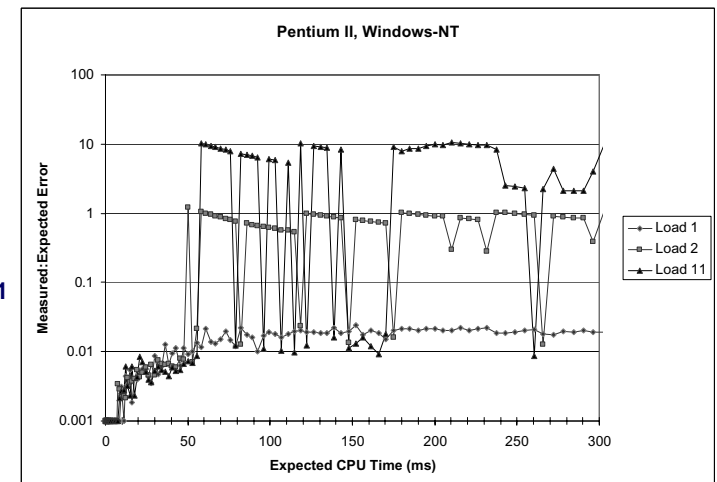
- Estimate overhead of single interrupt by measuring periods of inactivity
- Call interval timer to determine number of interrupts that have occurred

Better Accuracy for > 10ms

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

K-Best on NT

$K = 3, \epsilon = 0.001$



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

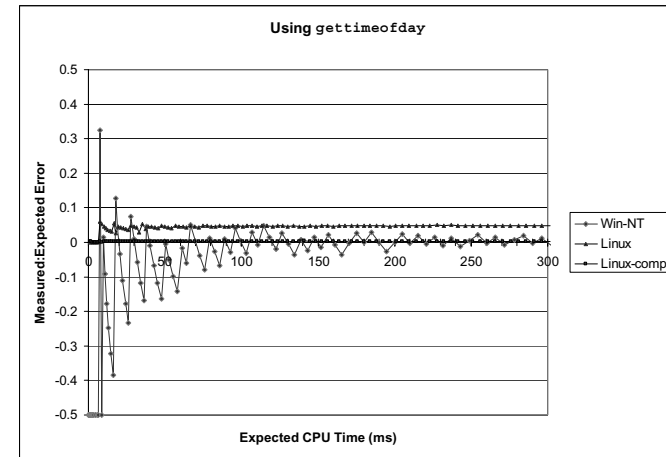
Time of Day Clock

- 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