Measuring Performance

Measurement tools and techniques

- Fundamental strategies
- Interval timers & cycle counters
- Indirect measurement

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Events

- Most measurement tools based on *events*
  - Some predefined change to system state
- Definition depends on metric being measured
  - Memory reference
  - Disk access
  - Change in a register's state
  - Network message
  - Processor interrupt

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Event Classification

- ***Count*** metrics
  - The number of times event X occurs
  - Number of cache misses
  - Number of I/O operations

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Event Classification

- ***Secondary-event*** metrics
  - Record a value when triggered by some event
  - Record block size for each I/O operation
  - Count number of operations
  - Find average I/O transfer size

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Event Classification

- ***Profiles***
  - Characterization of overall behavior
  - Aggregate/big picture view of an application program
  - Time spent in each function

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Event-Driven Strategies

- Record necessary information *only when selected event occurs*
- Modify system to record event
- Dump data when program terminates
  - May need intermediate dumps also
- E.g. simple counter in page fault routine

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Event-Driven Strategies

- System overhead
  - Only when the event of interest actually occurs
  - Infrequent events → little perturbation
  - Frequent events → high perturbation
- No longer "typical" behavior?
  - Perturbation changes system being measured

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Event-Driven Strategies

- Inter-event time is unpredictable
  - Depends on when events actually occur
  - Makes it hard to estimate perturbation
  - How long to measure?
- Event-driven measurement tools
  - → Good for low-frequency events

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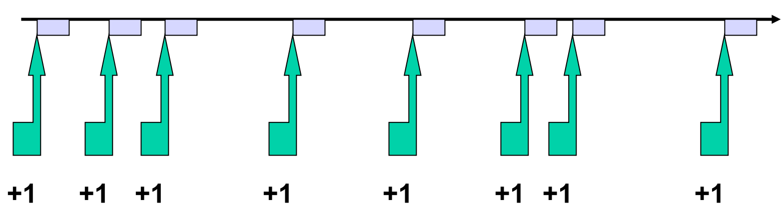
Event-Driven Strategies



- Counts 8 events exactly

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Tracing

- Similar to event-driven
- But record additional system state
  - Event has occurred – count
  - Additional information to uniquely identify event
  - E.g. addresses that cause page faults
- Overhead
  - Additional memory or disk storage
  - Time to save state
- Relatively large system perturbation

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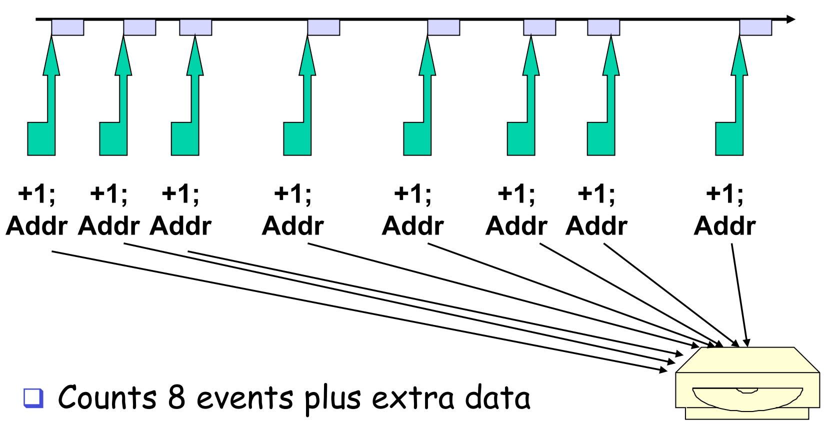
Tracing



- Counts 8 events plus extra data

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Sampling

- Record necessary state at fixed time intervals
- Overhead
  - Independent of specific event frequency
  - Depends on *sampling frequency*
- Misses some events
- Produces statistical summary
  - May miss infrequent events
  - Each replication will produce different results

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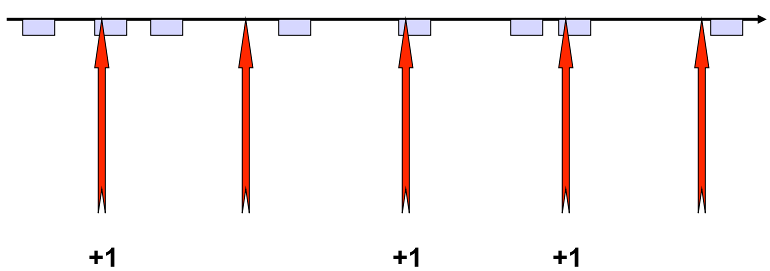
Sampling



- Counts 3 events out of 5 samples

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Comparisons

	Event count	Tracing	Sampling
Resolution	Exact count	Detailed info	Statistical summary
Overhead	Low	High	Constant
Perturbation	~ #events	High	Fixed

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Comparison

- Event counting
  - Best for low frequency events
  - Required if exact counts needed
- Sampling
  - Best for high frequency events
  - If statistical summary is adequate
- Tracing
  - When additional detail is required

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Indirect Measurements

- Used when desired metric is not directly accessible
- Measure one thing directly
  - Derive or deduce desired metric
- Highly dependent on creativity of performance analyst

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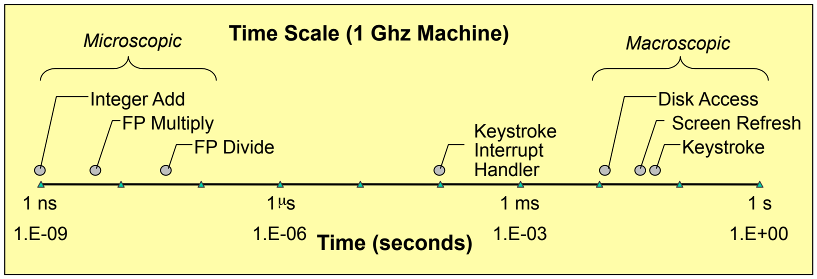
Time Measurement

Based on Ch 9 of Computer Systems: A Programmer's Perspective - Bryant & O'Halloran

Computer Time Scales



- Two Fundamental Time Scales
  - Processor: $\sim 10^{-9}$ sec.
  - External events: $\sim 10^{-2}$ 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

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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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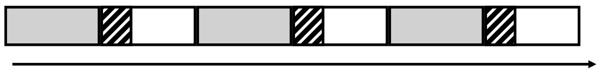
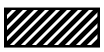
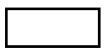
"Time" on a Computer System

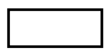


real (wall clock) time

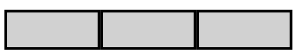
 **= user time** *(time executing instructions in the user process)*

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

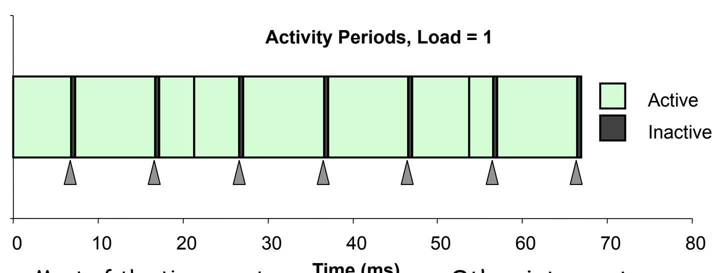
 **= some other user's time** *(time executing instructions in different user's process)*

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

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

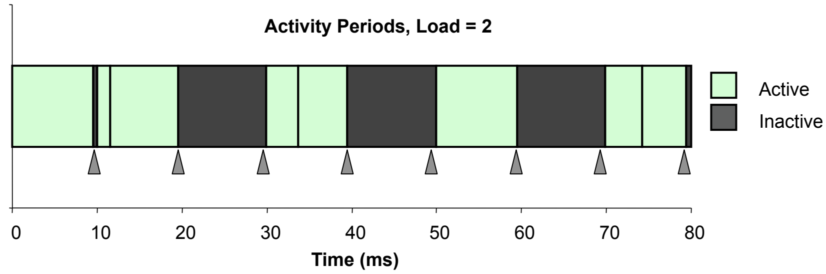
 **cumulative user time**

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

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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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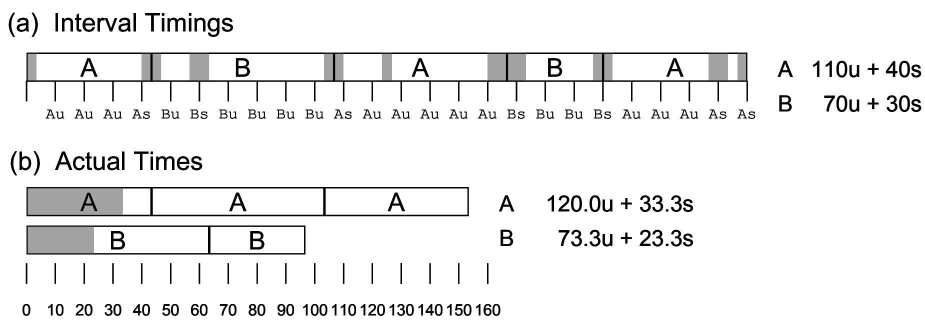
Interval Counting Example



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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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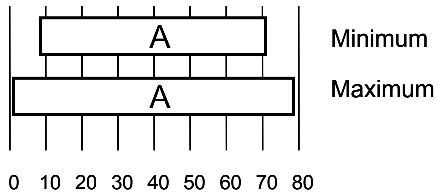
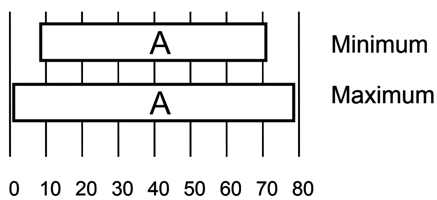
Accuracy of Interval Counting



- **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 ±δ
  - No bound on error for multiple segments
    - Could consistently underestimate, or consistently overestimate

Accuracy of Int. Cntg. (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

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);
}
```

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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

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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;
}
```

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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 */
```

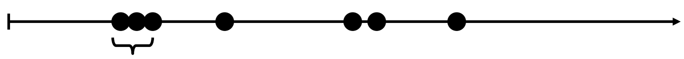

Dealing with Overhead & Cache Effects

- 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);
```

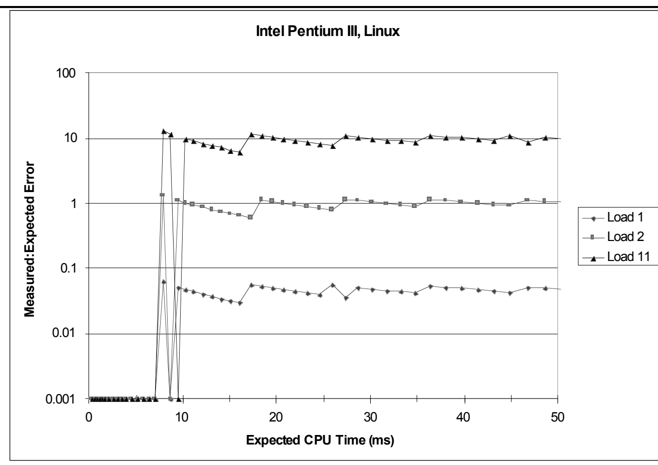
Multitasking Effects

- 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

How are "actual" run times of programs determined?

- Write a procedure that repeatedly writes values to an array of 2048 integers and then reads them back
- Let r be the number of repetitions
- Determine expected run time T(r) of procedure as a function of r by timing it for r = 1…10 and performing a least squares fit to T(r) = mr + b
  - Linear regression (will discuss later this semester)

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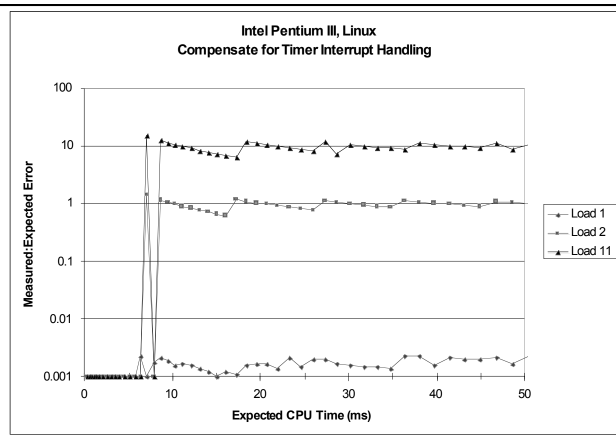
Compensate For Timer Overhead



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

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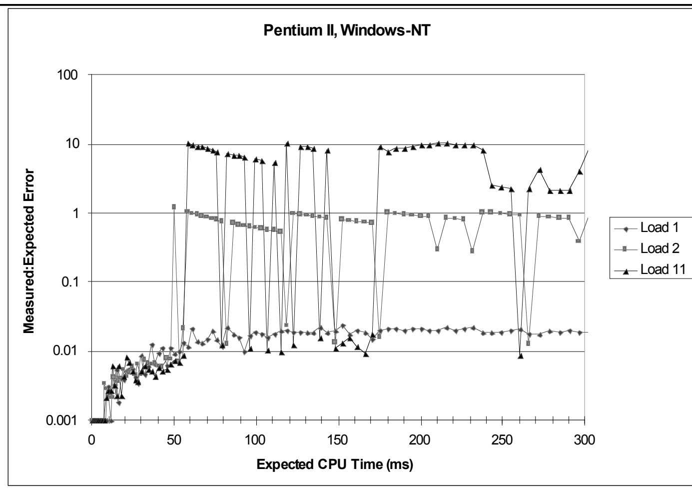
K-Best on NT

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

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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);
```

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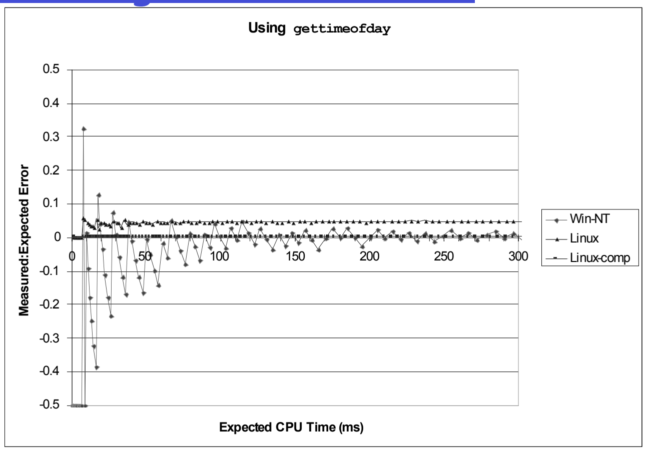
K-Best Using `gettimeofday`



- Linux
  - As good as using cycle counter
  - For times > 10 microseconds
- Windows
  - Implemented by interval counting
  - Too coarse-grained

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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

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Approximate Measures of Short Intervals

- Suppose no access to cycle counters
- How to measure an event that is shorter than the resolution of the clock?
- Cannot directly measure events with $T_e < T_c$
- Overhead makes it hard to measure even when $T_e > nT_c$,
  - *n* is small integer

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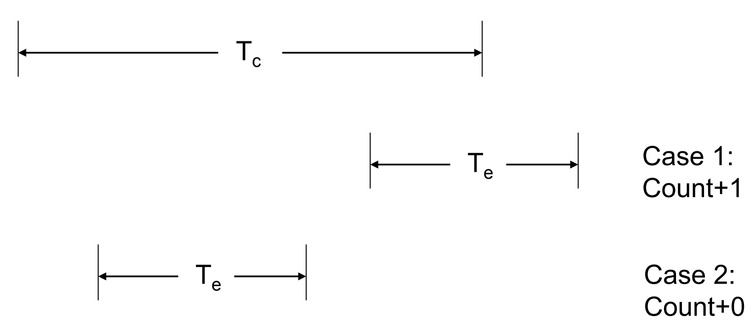
Approximate Measures of Short Intervals



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Approximate Measures of Short Intervals

- Bernoulli experiment
  - Outcome = +1 with probability *p*
  - Outcome = +0 with probability (1-*p*)
  - Equivalent to flipping a biased coin
- Repeat *n* times
  - Approximates a binomial distribution
  - Only approximate since each measurement cannot be guaranteed to be independent
    - Usually close enough in practice

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Approximate Measures of Short Intervals

- *m* = number of times Case 1 occurs
  - Count+1
- *n* = total number of measurements
- Average duration is ratio of *m/n*
- Use confidence interval for proportions

$$T_e = \frac{m}{n} T_c$$

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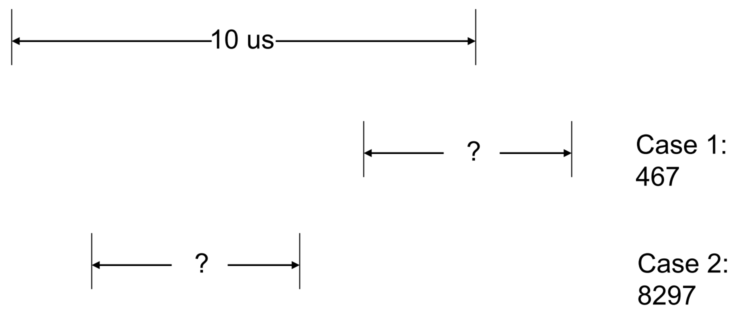
Example

- Clock resolution = 10 us
- n = 8764 measurements
- m = 467 clock ticks counted
- 95% confidence interval



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Example

$$(c_1, c_2) = \frac{467}{8764} \mp 1.96 \sqrt{\frac{\frac{467}{8764}\left(1 - \frac{467}{8764}\right)}{8764}}$$

$$= (0.0486, 0.0580)$$

- Scale by clock period = 10 us
- 95% chance that measured event is
  - (0.49, 0.58) us

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Important Aside

- Confidence interval calculation for proportions discussed in last class (and textbooks) is controversial
  - Recently, statisticians have shown that it is problematic
  - The approach used on the previous slide + in the textbooks (Lilja, Jain, others) is somewhat discredited
  - Link on class web page

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Indirect *Ad Hoc* Techniques

- Sometimes the desired metric cannot be measured directly
- Use your creativity to measure one thing and then derive/infer the desired value

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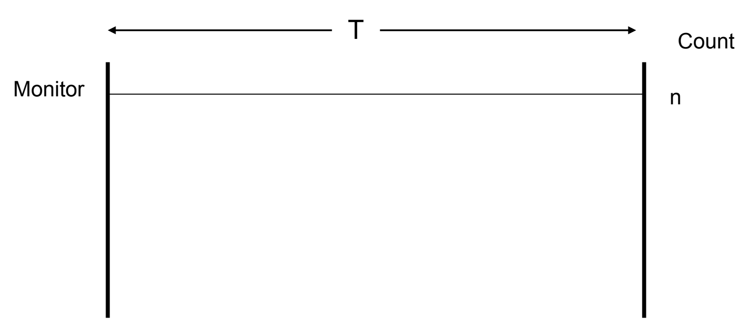
Example 1 – System Load

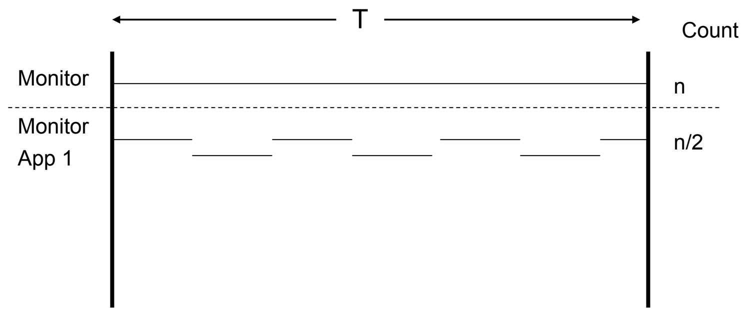
- What is system load?
  - Number of jobs in run queue?
  - Number of jobs actively time-sharing?
  - Fraction of time processor is not in idle loop?
  - Others?
- How to measure it?
  - Modify OS
  - PC sampling
  - Indirect?

Example



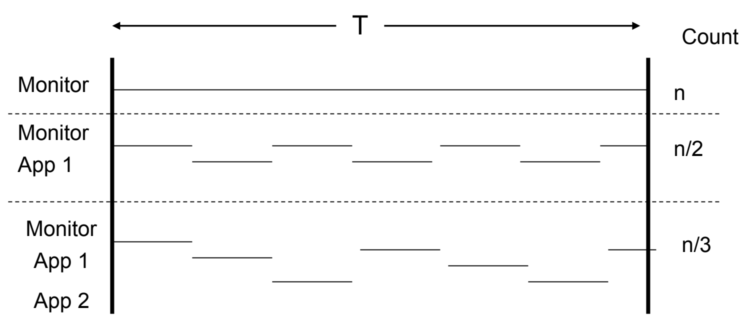
- Let system run for fixed time *T*
- Note value of counter

Example



- Let system run for fixed time *T*
- Compare value of loaded system monitor counter to unloaded system count value

Example



- Let system run for fixed time *T*
- Compare value of loaded system monitor counter to unloaded system count value

Example 2: The Memory Mountain

- Read throughput (read bandwidth)
  - Number of bytes read from memory per second (MB/s)
- Memory mountain
  - Measured read throughput as a function of spatial and temporal locality.
  - Compact way to characterize memory system performance.

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Memory Mountain Test Function

```
/* The test function */
void test(int elems, int stride) {
    int i, result = 0;
    volatile int sink;

    for (i = 0; i < elems; i += stride)
        result += data[i];
    sink = result; /* So compiler doesn't optimize away the loop */
}

/* Run test(elems, stride) and return read throughput (MB/s) */
double run(int size, int stride, double Mhz)
{
    double cycles;
    int elems = size / sizeof(int);

    test(elems, stride);                     /* warm up the cache */
    cycles = fcyc2(test, elems, stride, 0);  /* call test(elems,stride) */
    return (size / stride) / (cycles / Mhz); /* convert cycles to MB/s */
}
```

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Memory Mountain Main Routine

```
/* mountain.c - Generate the memory mountain. */
#define MINBYTES (1 << 10)  /* Working set size ranges from 1 KB */
#define MAXBYTES (1 << 23)  /* ... up to 8 MB */
#define MAXSTRIDE 16        /* Strides range from 1 to 16 */
#define MAXELEMS MAXBYTES/sizeof(int)

int data[MAXELEMS];         /* The array we'll be traversing */

int main()
{
    int size;        /* Working set size (in bytes) */
    int stride;      /* Stride (in array elements) */
    double Mhz;      /* Clock frequency */

    init_data(data, MAXELEMS); /* Initialize each element in data to 1 */
    Mhz = mhz(0);              /* Estimate the clock frequency */
    for (size = MAXBYTES; size >= MINBYTES; size >>= 1) {
        for (stride = 1; stride <= MAXSTRIDE; stride++)
            printf("%.1f\t", run(size, stride, Mhz));
        printf("\n");
    }
    exit(0);
}
```

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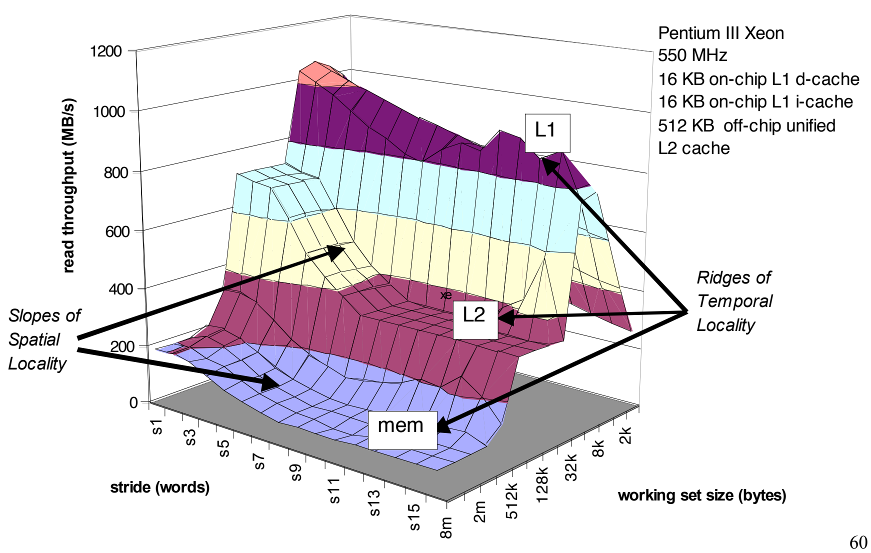
The Memory Mountain



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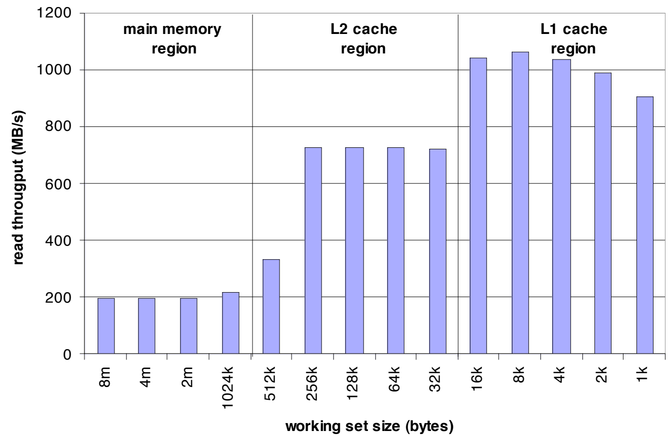
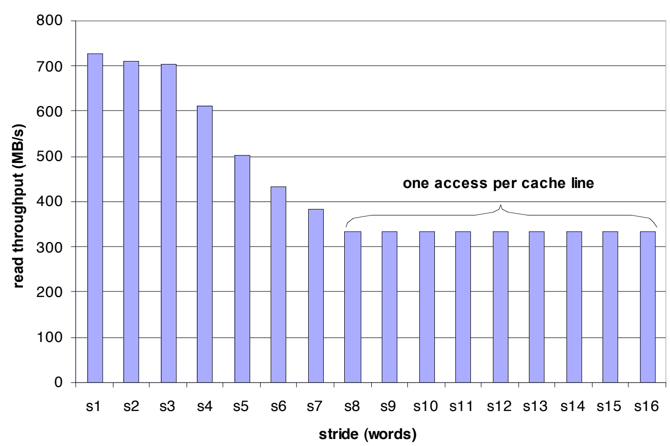
Ridges of Temporal Locality

- Slice through the memory mountain with stride=1
  - illuminates read throughputs of different caches and memory



A Slope of Spatial Locality

- Slice through memory mountain with size=256KB
  - shows cache block size.



Perturbation

- To obtain more information (higher resolution)
  - → Use more instrumentation points
- More instrumentation points
  - → Greater perturbation

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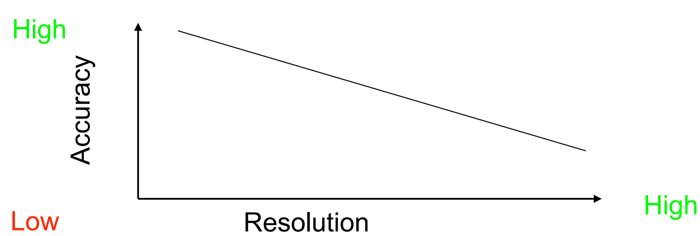
Perturbation

- Computer performance measurement uncertainty principle
  - ***Accuracy is inversely proportional to resolution.***



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Perturbation

- Superposition does not work here
  - Non-linear
  - Non-additive
- Double instrumentation ≠ double impact on performance
  - Some instrumentation cancels out
  - Some multiplies impact
- No way to predict!

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Instrumentation Code

- Changes memory access patterns
  - Affects memory banking optimizations
- Generates additional load/store instructions
  - More frequent cache flushes and replacements
  - But may reduce set associativity conflicts
- Generates more I/O operations
- Will increase overall execution time
  - More time-sharing context switches
- Alters virtual memory paging behavior

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Summary

- Measurement strategies
  - Event-driven
  - Tracing
  - Sampling
- Measuring program time
- Profiling
- Trace generation
- Indirect measurements when all else fails
  - System load example
- Perturbations
  - Have to be careful to minimize perturbations due to instrumentation

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